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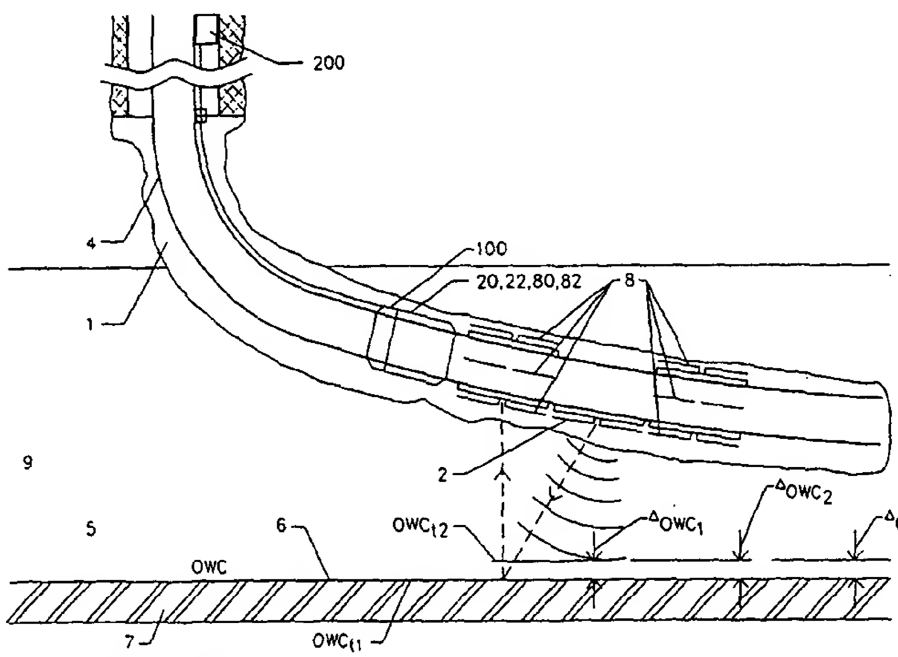
(57) Abstract



OWC - OIL-WATER CONTACT

The invention is a method for radar detection in a well (1) in a geological formation (9), comprising the following steps: i) emplacement of at least one transmitter antenna (2) in a fixed position and orientation in the well (1); ii) generation of a first series of electrical signals (25) to a transmitter antenna (2) and emission of a first series of electromagnetic waves (26_1) from the transmitter antenna (2) at a time (t_1); iii) reception of a first series of reflected electromagnetic waves (85_1, 85_2, ..., 85_n), by at least one, preferably more receiver antennas (8_1, 8_2, ..., 8_n), optionally signal amplification and transformation of the reflected electromagnetic waves to registrations (S_1); iv) generation of a second series of electrical signals (25) to the transmitter antenna (2) and emission of a second series of electromagnetic waves (26_2) from the transmitter antenna (2), by a later point of time (t_2), with the time difference t_2–t_1 being typically several hours or days or longer time; v) reception of a second series of reflected electromagnetic waves (85_1, 85_2, ..., 85_n) by the receiver antennas (8_1, 8_2, ..., 8_n), optionally signal amplification and transformation of the reflected electromagnetic waves to registrations (S_2).

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METHOD AND DEVICE FOR DETECTION OF EM WAVES IN A WELL.

Introduction

This invention relates to a method for use of a radar-like device in production wells, arranged for detecting the oil/water contact in a reservoir rock.

More specifically the invention comprises a method for using a transmitter antenna for electromagnetic waves which is fixedly arranged near a production tubing inside a geological formation, and receiver antennas which also are fixedly arranged near the production tubing, preferably by cement fixation in the well. This method and the application of the radar-like device may enable the user to detect reflectors constituted by electrically conducting surfaces inside the reservoir. Such a surface of particular importance is the oil/water contact, with the water front in most instances constituting a relatively sharp transition between oil filled sand with high resistivity, to water filled sand with low resistivity thereby constituting a reflector.

The known art.

Borehole logging tools utilising the radar principle is known from US. pat. 4 670 717, US. pat. 4 814 768, US. pat. 4 297 699, US. pat. 4 430 653 and GB 2 030 414. Some of these patent use methods where it is necessary to estimate a wave propagation speed in order to be able to interpret the radar signals.

Schlumberger's US-patent 5 530 359, "Borehole logging tools and methods using reflected electromagnetic signals", describe a logging tool with pulsed radar signals being transmitted from a transmitter antenna i a separate vertical section. The logging tool is freely hanging in the borehole in a cable or in a coiled tubing. Linear antenna elements are applied, being arranged parallelly with the long axis z of the tool. Electromagnetic pulses are emitted with a centre frequency of 40 MHz and a highest frequency component of 120 MHz. This pulse is emitted in all directions into the formation and reflected from structures in the formation back to the tool in the borehole. The transit time of the

pulse out to the structure and back to the tool is used for determining the distance between the reflecting structure and the borehole. Directional information is obtained by the fact that receiver antennas are arranged around the entire circumference of the tool, so that one may find the direction to the reflecting structure by making differences between the reflected signals. These differences may be calculated by means of electronic circuits, or subtraction may be performed by directly differentially coupled receiver antennas. One method to calculate the reflected signals' direction is given. A disadvantage by Schlumberger's patent 5 530 359 is that the instrument applies pulsed electromagnetic waves. This entails a spread of the frequency components already in the emitted signal, and thus the emitted signal pulse gets a continuously varying group velocity. The reflected signal becomes smeared out and one gets an unclear image of the reflecting structures. Near reflecting structures will also dominate over more remote reflecting structures, so that the more remote structures very hardly can be detected if the nearer rocks have relatively high conductivity / low resistivity. Another disadvantage by Schlumberger's instrument is that it is not fixedly arranged by the geological formation, so that there is no provision for tracing changes in electrical parameters in the formation during a period of time, e.g. from one date to another. The instrument is also not arranged for being applied neither in production wells nor in injection wells.

Another apparatus is described in US pat. 5 552 786: "Method and apparatus for logging underground formations using radar", (Schlumberger). US. pat. 5 552 786 describes a logging tool which partially solves the problem of the electromagnetic wave propagation speed in the formations which are to be logged. The apparatus emits an electromagnetic pulse in clos contact with the borehole wall, into the formation and receives the direct wave in a predetermined distance along the drillstring from the transmitter. Thereby the wave propagation speed for the "direct wave" through the rocks (which may be invaded by drilling mud), and the reflectors separations from the emitter/receiver system may be calculated more exactly than

if one had only an estimate of th wave propagation speed.

US. pat. 4 504 833 "synthetic pulse radar system and method" concerns a synthetically pulsed radar which generates several signals of different frequencies simultaneously. The response from the subsurface to these different frequencies simulates parts of the Fourier spectrum which would have been measured if one emitted a very short pulse which according to the mathematical background would have been very broad in the frequency spectrum. The system is however arranged to, among other things, to be used on board a vehicle because, according to its claim 1, it shall be able to generate all the component signals simultaneously.

US. pat. 4 275 787 "Method for monitoring subsurface combustion and gasification processes in coal seams" describes a radar for detecting a combustion front in a geological formation, e.g. a coal bearing formation. Due to the resistivity generally increasing with the temperature, such a combustion front will provide high resistivity and constitute a very large contrast in relation to the coal bearing formation which normally will show low resistivity. The attenuation exceeds 100 dB/wavelength in the combustion front, and the attenuation of "Pittsburgh coal" is 1 dB/wavelength, for "British coal" the attenuation is 3 dB/wavelength. The applicant (of US. pat. 4 275 787) mentions that a detection range for the combustion front is 100 m, an unrealistically long distance when one takes into consideration the conditions in an oil well where the attenuation of the signal is much higher and where it is a very difficult task to detect reflecting surfaces only one to two metres out in the reservoir. A swept signal is emitted and which varies continuously between a lowest and a highest frequency. Because the combustion front is moving, one may by subtraction of the received signals be able to see a change in the difference signal between the observations. However the patent does not take into consideration the need for tuning of the transmitter antennas when the transmitter antennas are lying very close to, e.g. a few millimetres from a metallic pipe surface (e.g. liner pipe or completion pipe) and the frequency of

the emitted signal shall be changed.

Statement of problem: Expected electrical properties on the background of logs.

The invention is made partially on the background of the expected problems which one may think can arise in context of petroleum production on the Troll oilfield in the North Sea. Below a description will be given, how the resistivities in the actual geological formations are relatively lower with respect to the conditions described in the known art, and therefore impractical to perform detection by means of electromagnetic waves by means of the known art.

Expected resistivity.

A map over the Troll oilfield, generally covering the license blocks 31/2, 31/3, 31/5 and 31/6 are shown in Fig. 3a. Resistivity data are available from five wells: 31/2-2 (Fig. 3b), 31/2-4 (Fig. 3c), 31/2-5 (Fig. 3d), 31/2-6 (Fig. 3e), and 31/2-7 (Fig. 3f). The graphs display resistivity in Ωm as a function of logging depth in mainly vertical boreholes through the reservoir rocks. The oil/water contact, hereafter called "OWC", is defined in the wells at the depths indicated in the respective figures. The distribution of resistivity with respect to depth is markedly different from well to well. In 31/2-2 the resistivity R varies between 3 Ωm and 13 Ωm over the OWC, while R in well 31/2-4 decreases from 100 Ωm to 1 Ωm over the OWC. In well 31/2-5 the resistivity varies between 40 Ωm and 80 Ωm before it starts to decrease in a monotonous way, about 1 metre above the OWC. At the OWC the resistivity R falls to about 7 Ωm. The development in well 31/2-6 is characterized by a relatively strong ripple between 8 Ωm and 14 Ωm, ev n though the decrease of resistivity is clear at the OWC. Well 31/2-7 has a low and relatively less varying R in the area between 7 metres above the OWC and down to the OWC, with a maximum of 2 Ωm and is evenly falling to 0,4 Ωm just before the OWC.

The resistivity graphs show that local variations in R may be much larger than the drop in R which takes place at

the OWC. Because the conductivity in the formations generally arise from salt water in the pore spaces or conductive schists, local variations may be due to varying reservoir quality embodied by a combination of clay mineral content and porosity. Parameters like local lithology, texture, facies and excess pressure will also affect the resistivity. Resistivity tools are generally quite exact and give repeatable measurements. Generally the depth resolution is small, about 10 cm. per measurement point, and the logs are smoothed to a certain degree due to the contact assembly of the instrument, so that the local formation resistivity will vary more than what is shown by the logs.

Expected dielectric.

No dielectric logs from the Troll oilfield are available. Here, dielectric data based on estimates of the known dielectric properties in sandstone, oil and water are applied. We select $\varepsilon_{rock}=7$. When δ is 0.20 (20% porosity) then $\varepsilon_{ro}=5.82$, showing that $\varepsilon_{ro}=6$ is a reasonable estimate for the dielectric constant for oil saturated sandstone.

The dielectric constant for sea water, $\varepsilon_{water}=80$ (King & Smith, 1981) at the frequencies actual for application in connection with this invention. The dielectric constant in water saturated sandstone is $\varepsilon_{rw}=13$. Figs. 4a, b, c, d and e show estimated distributions of relative dielectric values based on the water saturation of a 5 metres transition zone over the OWC in the same wells as for the figures 3b-f. The scale indicating the relative dielectric constant, ranges from about 6 to about 13.

Wave propagation in a conductive transition zone.

Fig. 5a displays an attenuation graph of electromagnetic waves in the frequency range between 1 MHz and 200 MHz. $\varepsilon_r=6$ and the resistivity R_{DC} is varied in steps of 5 Ωm from 5 Ωm to 30 Ωm. The rocks become more "transparent" for electromagnetic radiation the higher the resistivity is. Fig. 5b with the same frequency range displays graphs for constant $R_{DC}=30$ Ωm and with ε_r varying from 6, 8, 10, 12, 14 to 16. One will see that the dielectric constant has less influence on the attenuation

than the resistivity. The figures show that the attenuation is more than 10 dB/m for 30 Ωm and frequencies above ca. 12 MHz. Attenuation above 10 dB/m will result in more than 100 dB attenuation for a return ray from a reflector being 5 metres away.

Fig. 5c displays an enlarged section of the frequency range from Fig. 5a, between 1 and 16 MHz. The attenuation is still high for resistivities lower than 10 Ωm even in this low frequency range. Fig. 5d display the waves' phase velocities as a function of frequencies between 1 and 16 MHz. On the background of the attenuation the frequencies which are applied in a preferred embodiment of the invention will be between 1 and 16 MHz. Within this frequency band the phase velocity varies strongly with resistivity, which may result in strong dispersion of an electromagnetic signal with a wide frequency content.

Reflection, Backscattering.

All horizons in the well with electromagnetic resistivity contrast will result in reflections. Particles with higher conductivity, e.g. metal oxides, will **incur dispersion** of the electromagnetic waves. Near horizons will be detected more strongly than remote horizons if the resistivity contrast is the same, due to approximately spherical **geometrical dispersion**. This means that the reflexes from the resistivity contrast by the OWC may be masked behind numerous strong reflexes from local resistivity contrasts in the sandstone in the oil zone above the OWC. As an example, the resistivity contrasts represented by the gradients in R at 1578 metres and by 1580,5 metres depth in Fig. 3e will give strong reflexes initially not being different from the reflex from the OWC.

The purpose of the invention.

A purpose of this invention is to provide a system to measure the depth of the oil/water contact or the gas/water contact in a petroleum reservoir by means of electromagnetic waves.

Another purpose is to bring forward an instrument arranged to register and map the distribution of resistivity

in the petroleum reservoir surrounding the well, to apply these resistivity measurements in geological interpretations of the reservoir.

Definition of the invention; reference to the set of claims.

The above mentioned problems may be solved by means of the present invention, which is a method for radar detection in a well (1) in a geological formation (9) characterized in that it comprises the following steps:

i) arrangement of at least one transmitter antenna (2) in a fixed position and direction in the well (1) with respect to the geological formation (9);

ii) generating a first series of electrical signals (25) to a transmitter antenna (2) and emission of a first series of electromagnetic waves (26_1) from the transmitter antenna (2) at a first time (t_1);

iii) reception of a first series of reflected electromagnetic waves ($85_1, 85_2, .., 85_n$) by at least one, preferably several receiver antennas ($8_1, 8_2, .., 8_n$), and transformation of the first series of reflected electromagnetic waves preferably to digital registrations (S_1);

iv) generating a second series of electric signals (25) to the transmitter antenna (2) and emission of electromagnetic waves (26_2) from the transmitter antenna (2), still in the same position and direction in the well (1), at a later point of time (t_2), with the time difference t_2-t_1 typically being several hours, days or longer time;

v) reception of a second series of reflected electromagnetic waves ($85_1, 85_2, .., 85_n$) by the receiver antennas ($8_1, 8_2, .., 8_n$), and **transformation** of the second series of reflected electromagnetic waves preferably to digital registrations (S_2).

The invention is also a device for radar detection in a well in a geological formation, with the new and inventive by the invention being:

(a) at least one transmitter antennas for emission of electromagnetic waves, attached near a tubing string, being arranged for fixed mounting with respect to the geological

formation, and

(b) at least one, preferably several receiving antennas for reflected electromagnetic waves, near preferably the first string of pipes, and which is also being arranged for fixed emplacement with respect to the geological formation.

Additional features of the invention are given by the dependent claims.

Description of the figures.

The invention will be described in detail in the paragraphs below, with non-limiting examples of preferred embodiments of the invention, with reference to the accompanying drawing figures of the non-limiting examples, with:

Fig. 1 describing a part of a production well with production tubing in a geological production zone for petroleum fluids, with oil or gas above in the production zone, and water below.

Fig. 2 displays a schematic illustration with an embodiment of the invention being arranged by a production tubing.

Fig. 2b illustrates a section of a preferred embodiment of the invention, as a module comprising transmitter- and receiver antennas and which may enter as an ordinary screw-threaded part of the completion in the production zone.

Fig. 2c displays in perspective view the module of Fig. 2b, having outer conical threading at the top and corresponding inner conical threading in the lower part.

Fig. 3a displays a map over license blocks on the Troll oilfield in the North Sea, and Figs. 3b, c, d, e and f display logs of resistivity as a function of depth in five vertical boreholes in the Troll oilfield.

Fig. 4a, b, c, d and e display estimated distributions of relative dielectric values based on water saturation in a 5 metres transition zone over the OWC in the same wells as the Figs. 3b-f. The scales have 13 as their highest value, indicating full water saturation in a 20% porous rock.

Fig. 5a display theoretical graphs of electromagnetic waves' attenuation as a function of frequencies between 1 MHz and 200 MHz, for rocks with various conductivity or

resistivity.

Fig. 5b displays theoretical graphs of electromagnetic waves' attenuation as a function of frequencies between 1 MHz and 200 MHz, for rocks with various dielectric constants.

Fig. 5c displays the same as Fig. 5a, but narrowed to a frequency range between 1 and 16 MHz.

Fig. 5d displays theoretical graphs of phase velocity as function of frequency between 1 and 16 MHz.

Fig. 5e displays graphs over wavelength as a function of frequencies between 1 and 16 MHz for resistivities varying between 5 Ωm and 25 Ωm.

Fig. 6a show graphs of emitted electromagnetic waves' amplitude with respect to the delayed time since the start of the emission.

Fig. 6b display corresponding graphs of received electromagnetic signals at receiver antennas. The signals are reduced in amplitude, and phase displaced with respect to the emitted signals.

Fig. 6 c and d describe schematically a part of a method according to a preferred embodiment of the invention, with formation of frequency spectra of the registered signals from reflectors.

Fig. 6e describe schematically a part of a method according to a preferred embodiment of the invention, with formation of an artificial time-distance measurement to a reflector.

Fig. 7 and Fig. 8 display an application of a preferred embodiment of the invention for detecting of change of the distance between the radar and several sections of an oil/water contact OWC.

Fig. 9 is a large-perspective illustration of a well with corresponding surface arrangement, with the well comprising transmitter- and receiver antennas in an horizontal production zone with varying distance to the oil/water contact OWC.

Fig. 10 illustrate several devices according to the invention in a perforated horizontal production well.

Fig. 10b and 10c show illustrations of a device and a method according to the invention in an alternative

application in a vertical well.

Detailed description of the invention.

The well.

Fig. 1 shows a production well or a borehole 1 in a geological formation, which may be situated onshore or below the seabed. Usually there will be inserted a steel casing in several sections down in the drilled hole from the seabed and down to the top of the formation producing petroleum fluids as oil or natural gas. The producing formation may be without casing pipe, a so-called open completion, or have a casing made in composite material being transparent to electromagnetic waves. In a preferred embodiment of this invention one will not set a casing pipe in the production zone, but perform a cementing-in of a production pipe in the well 1. The geological formation comprises in this connection a reservoir rock, e.g. a porous, permeable sandstone formation 9. The borehole 1 may be more or less deviation drilled and is displayed in the figure as a near-horizontal borehole 1 even though the invention may be applied in boreholes with all deviation angles from the vertical direction downwards, between 0 and 180 degrees. A production tube 4 is arranged for completion of the production well or borehole. The production pipe's 4 diameter may be 7" in a 8 1/2" borehole 1. A lining pipe (not shown) is usually arranged outside the production pipe 4. The lining pipe may be cemented and perforated, or consist of a fine mesh retaining sand and letting through oil, gas and water. A preferred embodiment of the invention will be applied in a nearly horizontally drilled well 1 in a sandstone formation 9. An oil/water contact OWC constitutes the interface between the substantially oil saturated sandstone 5 and water saturated sandstone 7. This invention may also be applied in an injection well or in an observation well. The fixed arrangement of the antennas by the geological formation may in one embodiment take place by cementing, implying that possible fluid flow between the antenna and the formation is brought to a halt, and that the wellstream thus possibly must take place inside the well tubing. By bringing the wellstream between the antenna and

the geological formation to al halt, changing electromagnetic properties of the fluid in the wellstream will not disturb the emitted or received electromagnetic signals. Due to the legibility of the drawings it is not indicated that the antenna and the tubing may be entirely or partially cemented-in along the well.

The method according to the invention.

A preferred embodiment of the invention is a method for radar detection in a well 1 in a geological formation 9. The method comprises the following steps, with reference to figure 2 and figure 7 and 10:

i) one arranges at least one transmitter antenna 2 in a fixed position and **attitude** in the well 1 with respect to the geological formation 9. (The fixation may be performed by means of arranging the transmitter antenna 2 on the outer side of a pipe string 4, e.g. a production tubing 4 or an injection tube 4 and guide the tubing string 4 down into the well 1, and thereafter cement the tubing string 4 by ordinary injection of cement in the annulus. In a preferred embodiment of the invention the transmitter antenna is arranged on modules 8' as shown in Figs. 2b and c, a feature which will be described in more detail below.)

ii) Generating a first series of electrical signals 25 to a transmitter antenna 2 and emission of a first series of electromagnetic waves 26_1 from the transmitter antenna 2 by a first point of time t_1. A preferred embodiment of the transmitter antenna 2 is a dipole antenna as shown in Fig. 2 and 7.

iii) Receiving a first series of reflected electromagnetic waves ($85_1, 85_2, .., 85_n$) at at least one, preferably several receiver antennas ($8_1, 8_2, .., 8_n$), and transformation of the first series of reflected electromagnetic waves to registrations S_1, with the registrations preferably being digitized. The receiver antennas 8 are also in the preferred embodiment dipole antennas.

iv) Generation of a second series of electrical signals 25 to the transmitter antenna 2 and emission of a second series of electromagnetic waves 26_2 from the transmitter antenna 2, still in the same position and **attitude** in the well 1, by a

later point of time t_2, with the time difference t_2-t_1 typically being several hours, days or longer time.

v) reception of a second series of reflected electromagnetic waves ($85_1, 85_2, .., 85_n$) by the receiver antennas ($8_1, 8_2, .., 8_n$), and transformation of the second series of reflected electromagnetic waves to registrations S_2, with the registrations preferably being digitized.

In a preferred embodiment of the invention the method comprises the additional following steps:

vi) Formation of a difference D_{t2-t1} by subtraction of the registrations S_1 from the registrations S_2. If the registrations are digital this is an especially useful method.

vii) interpretation of the difference D_{t2-t1} as the distance and possibly a direction to a horizon with a change of electrical properties between the points of time t_1 and t_2. Determination of the direction will be made possible by means of details by the method and the device as explained below. The distance is interpreted from two-way travel time (not the difference D_{t2-t1}) between the transmitter antenna 2, the expected reflector and the receiver antenna 8, with transit speed e.g. interpreted from Fig. 5d which gives group velocities for different frequencies. The interpretation of the difference D_{t2-t1} is performed by searching for changes in resistivity which may represent a displacement of a liquid horizon, e.g. an oil/water contact OWC. The result of such a determination of a displacement distance of OWC is illustrated in the Figs. 7 and 8. In the invention it is expected that it will be only liquids which displace themselves during the time between the registrations S_1 and S_2, but there is a possibility that solid particles also may have been removed, e.g. by production of loose sand particles from the well, or by deposition of clay minerals in the pore spaces in the geological formation 9. These effects may complicate the interpretation of the registrations S_i, but the invention may also be applied for registering such change in the rocks.

In Fig. 6a is illustrated a preferred embodiment of the method according to the invention. Emission of coherent continuous electromagnetic waves 26_1 is made, from the

transmitter antenna 2. The advantage by this is that one at every instant during the emission only emits one single frequency, and thus achieves that the electromagnetic waves propagate at one single speed. By ordinary radars, pulses are emitted which, according to wave theories, e.g. Fourier analysis, will have an infinite number of frequencies within a wide band of frequencies. The shorter the pulse, the wider frequency band the pulse contains.

A most preferred embodiment of the method according to the invention is shown in Fig. 6a, and comprises emission of coherent continuous electromagnetic waves 26_1, 26_2 stepwise ("stepped"), by a number of i different frequencies f_1, f_2, ... , f_i from the transmitter antenna 2. In this way one may in a real way build up a frequency spectrum covering discrete frequencies f_1, f_2, ... , f_i being emitted into the geological formations 9. Each of the electromagnetic wave-trains will propagate through the medium with each their discrete velocity. Fig. 6b illustrates that a part of the reflected energy is received as reflected waves (85_1,85_2,.., 85_n) by the receiver antennas (8_1,8_2,.., 8_n), where they are transformed to preferably electrical voltage signals which may be amplified and digitized and represented by registrations S. In an alternative embodiment of the invention, the reflected waves (85_1,85_2,.., 85_n) may be transformed to optical signals at a selected stadium, possibly already in the antennas.

In a preferred embodiment of the method according to the invention it is very advantageous to perform impedance adjustment of the transmitter antenna 2 for each one of the discrete emitted frequencies (f_1, f_2, ... , f_i), for maximum power emission to the geological formation 9. This is because the transmitter antennas 2 Q-factor changes drastically by change of frequency when the transmitter antenna 2 is situated only a few centimetres from the metallic tubing string's 4 surface. (If the transmitter antenna 2 is not tuned for maximum emission of electromagnetic energy to the geological formation 9, large parts of the energy will travel like an electromagnetic wave along the tubing string 4, almost like a signal along a core of a coaxial cable, with the rocks around the tubing string

playing the role of the coaxial cable's dielectric.) A physical adaptation of the dipole antenna's length may happen via electronic switches which connects or disconnects more remote sections of the antenna in order for it to correspond to a quarter wavelength in the medium, and with the tuning of the antenna supplemented by tuning of the capacity of the resonance circuit by feedback connection.

A corresponding impedance adjustment of the receiver antennas 8 must be performed for each particular of the emitted discrete frequencies (f_1, f_2, ... , f_i), for maximum reception of power from reflected electromagnetic waves from the geological formation 9. An image of the needed antenna lengths is obtained by studying Fig. 5e which displays wavelengths as a function of frequency inside the range between 1 and 16 MHz.

Some direct coupling always occurs of the emitted wave from the transmitter antenna 2 to the receiver antenna 8. Cancellation of direct waves or directly coupled signals between the transmitter antenna 2 and the receiver antenna 8 should be made, such that the direct wave interferes minimally with the reflected waves from the geological formation 9. This may according to an embodiment of the invention take place e.g. by a differential coupling between receiver antennas 8, possibly a relative differential coupling between the signal from the receiver antenna 8 and a relatively attenuated part of the voltage signal 25 to the transmitter antenna 2. (In an alternative embodiment of the invention with pulsed waves being applied there is a possibility for cancelling of the direct wave by avoiding sampling the signal from the receiver antennas for a short time during and after the emission of electromagnetic waves 26 from the transmitter antenna 2, so that the direct wave will pass. The technique by sampling in time windows may also compensate for unwanted signals from very close or strong reflectors shadowing for remote-lying more interesting reflectors. However, the windowing technique is only advantageous during pulsed signal emission, which disadvantages are explained above.) During emission of continuous waves with duration comparable with two-way transit time to the reflector, a differential coupling

between the receiver antennas should be mad .

A signal processing of the received electromagnetic waves ($85_1, 85_2, .., 85_n$) or the registrations S_1 or S_2 is needed in order to detect changes in the electrical properties, preferably resistivity, in the geological formation 9.

In a preferred embodiment of the invention, a signal processing of the received electromagnetic waves ($85_1, 85_2, .., 85_n$) or the registrations S_1 or S_2 in order to detect changes in the electrical properties, preferably resistivity, in the geological formation 9 between two points in time t_1 and t_2. Figs. 6c, 6d and 6e display an example of such a signal processing of time series representing the reflected signals ($85_1, 85_2, .., 85_n$) or the registrations S_1 or S_2. In an embodiment of the method shown in Fig. 6c and Fig. 6d, at least one discrete Fourier frequency spectrum of at least two of the parameters amplitude $A(\omega)$, phase $f(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$. ω corresponds to the frequencies (f_1, f_2, ... , f_i) which were emitted from the transmitter antenna 2.

By emission of continuous coherent electromagnetic waves it is possible to perform a direct stepwise sampling of signals with amplitude $A(\omega)$, phase $f(\omega)$ of the electromagnetic waves ($85_1, 85_2, .., 85_n$) from the receiver antennas 8 in the frequency domain at the frequencies (f_1, f_2, ... , f_i). Thus a simplified registration of the electromagnetic waves ($85_1, 85_2, .., 85_n$) may be performed by essentially just to register the amplitude and phase of the incoming wave-train by each frequency f_1, f_2, ... , f_i. This requires less equipment than e.g. a discretely sampled digitizing of $f_i(t)$. Thus the step illustrated in the left part of Figs. 6c and 6d, represented by sampling of $f_1(t)$, $f_2(t), \dots, f_i(t)$, together with the fast Fourier transform, is omitted in this simplified example, where one starts directly with measurement of amplitude $A(\omega)$, phase $f(\omega)$ for each particular frequency. One embodiment of the invention comprises signal processing of an inverse Fourier transform $F(\omega) \rightarrow f(t)$ by inverse Fourier transforming at least two of the parameters amplitude $A(\omega)$, phase $f(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$, with

ω comprising essentially the frequencies f_1, f_2, ... , f_i, which were emitted from the transmitter antenna 2, and formation of a time series f(t) which may represent pseudo-reflexes formed by electric resistivity gradients in the geological formation 9.

In a preferred embodiment of the invention there is performed an arrangement of a directionally sensitive antenna group 8' comprising three or more receiver antennas 8 around the tubing string's 4 axis and essentially by the same longitudinal position at the tubing string 4, with the purpose to detect the electromagnetic waves (85_1,85_2,.., 85_n) and their reflectors' direction with respect to the tubing string's 4 axis. By combined reception of signals from receiver antennas 8 arranged at different angles, one may by combination of the received electromagnetic waves (85_1,85_2,.., 85_n), possibly by direct physical connection between receiver antennas 8 arranged in a directionally sensitive antenna group 8', calculate a reflector's angle α with respect to the tubing string's 4 axis.

By a corresponding arrangement of a transmitter antenna group 2' comprising two or more transmitter antennas 2, in this case preferably dipole-shaped transmitter antennas 2, around the tubing string's 4 axis and essentially at the same position along the tubing string 4, one obtains emission of electromagnetic waves 26 with energy propagating generally in a selected direction with respect to the tubing string's 4 axis. Thus one may "illuminate" a selected part of the geological formation. In the combination of the application of a directionally sensitive receiver antenna group 8' and a transmitter antenna group 2' one may perform a tomographic calculation of the electrical properties in a plane P perpendicular to the tubing string 4. This is illustrated in Fig. 2.

By combining signals (85_1,85_2,.., 85_n) from several receiver-antenna groups 8' (or alternatively signals (85_1,85_2,.., 85_n) received after emission from several transmitter antenna groups 2') one may in addition calculate a reflector's angle β normal to the plane P.

In an alternative embodiment of the invention, generation of electrical signals 25 for emission of pulsed electromagnetic

signals 26 from the transmitter antenna 2 may be made.

The radar device and the system as a unit is believed to have a dynamic range of 170 dB, with dynamic range being defined as emitted power divided by the least possibly registered received power. The electromagnetic waves will become attenuated due to propagation attenuation and wave dispersion and additionally there will be a geometrical dispersal of the power. It is assumed that one have a signal analyser with the least detectable signal is - 110 dBmw for IF (intermediate frequency filter bandwidth) = 10 Hz and maximum input without saturation is 20 dBmw. Thus the dynamic range for the signal analyser is 130 dB for IF = 10Hz. By reducing the IF-bandwidth (and by using continuous coherent waves) the dynamic range may be increased. The cost of this increased dynamic range is that the time used for signal reception will also increase. However one will have lots of time available for signal emission and reception while going to observe a change of the OWC. By selecting IF 0.1 Hz the least detectable signal becomes less than -130 dBmw and the signal analyser's dynamic range becomes 150 dB. Assume further that the applied power is 20 dB more than the coupled power. Thus the emitted power in the system according to an embodiment of the invention 170 dB more than the smallest detectable power. Emitted transmitter power is 10 W when the antenna efficiency is 1. Less antenna efficiency may be compensated for by higher transmitter power.

Assume that the receiver area A = 1 m^2 (for a dipole antenna of length 1 m) and R = 20 Ωm. The geometrical dispersion is thus 47 dB by a distance of 30 m. If we assume the dynamic range = 170 dB, geometric dispersion at a distance of 30 m to be 50 dB, reflection loss of 40 dB, then 80 dB remains for propagation loss. For a zone of resistivity R = 500 Ωm the propagation loss is approximately 1.2 dB/m. Thus the detection range may be calculated as 0.5/(80/1.2)>30 metres. Directivity of the antennas will increase the detection range.

The device according to the invention.

At least one transmitter antenna 2 for emission of

electromagnetic waves is fixedly arranged by the tubing string 4. The transmitter antenna 2 is arranged for fixed arrangement with respect to the geological formation. One or more receiver antennas 8 for electromagnetic waves is also arranged by the tubing string 4. The receiver antennas 8 are also arranged for fixed mounting with respect to the geological formation. The purpose of the fixed arrangement in the production zone is that measurements may be performed with some time's interval if it is difficult to detect horizons by means of pulsed radar measurements. If OWC has displaced itself in the time between the measurements one may, by means of subtraction of the measurements detect this change, and estimate the position of OWC.

The radar in the well.

Fig. 2 illustrates a principle illustration of a possible embodiment of the invention, with transmitter antennas 2 and receiver antennas 8 arranged near a production tube 4. If the production tube 4 is metallic and electrically conductive, which is the present case, the antennas 2 and 8 must be arranged in the annulus between the production tube 4 and the geological formation 9. In a preferred embodiment of the invention the antennas 2 and 8 will be cemented in the annulus in the production zone in the formation 9, so that they are absolutely fixed in position and attitude. This absolute fixation of position and attitude leads to measuring- and analysis advantages which do not exist in the known art.

The fixed arrangement may be performed in several ways: The antenna may be fixed to the outer surface of the tubing string 4, and cemented rigidly to the formation by means of cement. In one preferred embodiment of the invention displayed in Fig. 6b, transmitter antennas 2 and receiver antennas 8 are arranged in unitary tubing string antenna modules 4' which may be threading screw joined and acting as ordinary components in a tubing string 4 in a production well completion.

A preferred embodiment according to this invention will be applied in an almost horizontal well in a geological formation 9 as displayed in Fig. 1. Fig. 2 illustrates a

device for detection of electrical properties, comprising at least one transmitter antenna 2 for emission of electromagnetic waves 26, mounted by a tubing string 4, with the transmitter antenna 2 is arranged for fixed mounting with respect to the geological formation 9, at least one, preferably several receiver antennas 8 for the reflected electromagnetic waves 26, by preferably the same tubing string 4, with the receiver antennas 8 are arranged for fixed mounting with respect to the geological formation 9. The receiver antennas 8 must be arranged so close to the receiver antennas 2 that they under the prevailing surrounding resistivities may receive reflected electromagnetic waves.

A directionally sensitive antenna group 8' comprising three or more receiver antennas 8 is in a preferred embodiment arranged around the tubing string's 4 axis and essentially at the same position along the tubing string 4, arranged to detect the reflected electromagnetic waves 26 and their reflectors' direction with respect to the tubing string's 4 axis. Such directionally sensitive antenna groups 8' are shown by two groups of dipole antennas 8, having one antenna group 8' arranged on either side of the illustrated transmitter antenna 2. In this way reflected electromagnetic waves received by several receiver antennas 8 at each antenna group 8' may be combined to calculate a direction α for the reflector in the plane P being perpendicular to the tubing string's 4 axis through the antenna group 8'. This is illustrated in Fig. 2. The combination of the signals may take place via physically connecting antenna signals in order to achieve differences, or combinations may be performed digitally after registering the waves. Phase differences between the incoming signals may also be used for finding the angle α. An angle β with respect to the normal plane P may be calculated by combining reflected electromagnetic signals received by at least two receiver antennas 8 arranged with each their distance from the transmitter antenna, counted along the tubing string 4, and preferably on either side of the transmitter antenna 2. The angles α and β uniquely determine the direction to a reflector. A reflector's distance may be determined by

estimating a two-way travel time for an electromagnetic pulse. In this way a reflector's position may be calculated with respect to the tubing string and its transmitter antennas 2 and receiving antennas 8.

In the same manner it is advantageous with an embodiment with a transmitter antenna group 2' comprising two or more transmitter antennas 2 arranged around the axis of the tubing string 4 and essentially by the same position along the tubing string 4, arranged to emit electromagnetic waves mainly in a selected direction with respect to the tubing string's 4 axis.

Fig. 2b illustrates a preferred embodiment of the invention is transmitter antennas 2 and receiver antennas 8 combined in a tubing string module 4' comprising a transmitter antenna group 2' with at least two transmitter antennas 2 arranged by a first position along the tubing string antenna module 4', and at least one directionally sensitive group 8' with at least three receiver antennas 8 arranged by a second position along the tubing string module 4'. In the most preferred embodiment of the tubing string antenna module 4' it comprises a transmitter antenna group 2' with preferably two dipole-transmitter antennas 2 arranged on either side of the tubing string 4 by a first position along the tubing string antenna module 4', a first directionally sensitive group 8' with preferably four dipole-receiver antennas 8 arranged with even angular separation around the tubing string 4 by a second position along the tubing string antenna module 4', and a second directionally sensitive group 8' with preferably four dipole-receiver antennas 8 arranged in the same manner by a third position along the tubing string antenna module 4', preferably at the opposite side of the transmitter antenna group 2' relative to the first directionally sensitive group 8'.

Fig. 2c illustrates a perspective view of the tubing string antenna module 8'. The inner diameter will in the preferred embodiment be 4.9" and the metallic pipe 15 will have a diameter of 7". Ceramic isolators 6 are arranged outside on the metallic surface of the pipe 15. The ceramic isolators 6 constitute the base for transmitter antennas 2

and receiver antennas 8, respectively. In a preferred embodiment the isolators may be recessed in a cylinder-shaped recess in the metallic pipe 15. The entire side surface of the tubing string antenna module 8' is covered by a non-conductive coating in order to DC-isolate the electrical equipment from the well 1 and the geological formation 9. Centralizing devices are also arranged outside on each tubing string antenna module 4'. In a preferred embodiment the outer diameter for each centralizer is 9". This does not exclude other dimensions of the tubing string antenna module 4'. Electrical conductors 7 are arranged for energy supply and communication along the tubing string module 4', with means for electrical coupling between two or more tubing string modules 4' internally and also equipment other where, e.g. by the surface.

The tubing string antenna module 4' will usually constitute a part of a series of equal modules 4', together with other modular parts of a production tubing in a well completion string. The tubing string antenna module is arranged to preferably be cemented fixed in the well. The module 4' and the electrical conductors 7 must be marked, e.g. magnetically, so they are not destroyed during perforation shooting of the production tube.

An electronics package 20 comprising necessary equipment to run the radar consists of a signal generator 22 for generation of electrical signals 25 to the transmitter antenna 2, devices 80 for reception of signals ($85_1, 85_2, .., 85_n$) induced in each of the receiving antennas ($8_1, 8_2, .., 8_n$), signal processing devices 82 for processing of the received signals ($85_1, 85_2, .., 85_n$), and communication- and control devices 100 for emitting signals 105 which represent the electrical signals ($85_1, 85_2, .., 85_n$), and for reception of control signals 205. The control signals and energy supply may in a preferred embodiment take place from a communication device 200 by the surface, via the electrical conductors 7.

In a preferred embodiment of the invention, the electronics package 20 is situated immediately in the vicinity of the antennas 2, 8. In an additionally preferred embodiment illustrated in Fig. 7 the tubing string antenna

module 4' comprises the electronics package 20, and the electronics package 20 comprises (not shown) also an address unit 55, an accumulator- and charging unit 56, a memory 54 and a rest mode unit 57. The signal processing units 82 may be arranged for downhole processing of measured data. In the preferred embodiment each tubing string antenna module 4' will be addressable and selectively activated by the communication device 200. The accumulator- and charging unit 56 may collect energy enough for sufficient energy to be emitted out into the geological formations from the transmitter antennas 2 so that the receiver antennas 8 may register signals from reflectors. Due to power limitations of the energy- and communication conductors 7 the rest mode unit 57 is applied to engage different addressable electronics packages 20 with corresponding antennas 2, 8 at separate times, both with regard to charging, emission and processing.

In a preferred embodiment, the signal generator 22 for generation of electrical signals 25 to the transmitter antenna 2 will be arranged for generation of coherent continuous electromagnetic waves 26 from the transmitter antenna 2. Thus one may avoid dispersion of emitted electromagnetic signals due to varying group velocity as a function of the frequency. In an additionally preferred embodiment the signal generator 22 is arranged for generating electrical signals 25 to the transmitter antenna 2 for emission of coherent continuous electromagnetic waves by a number of *i* different frequencies $f_1, f_2, \ldots, f_i$ from the transmitter antenna 2.

An impedance regulating device 23 (not shown) arranged to adapt the transmitter antenna's 2 impedance to each particular of the discrete emitted frequencies $f_1, f_2, \ldots, f_i$ is necessary. This impedance regulating device 23 may be an electronic switch in the dipole antennas 2 themselves. The electronic switch adjusts the dipole antenna's 2 physical length. Alternatively, or as a supplement to switches on the antennas, one may perform tuning of the resonance circuits' capacitance by feedback coupling.

In a corresponding manner there is in the preferred

embodiment arranged an impedance regulating device 83 (not shown) arranged to adapt the receiver antenna's 8 impedance to each particular of the emitted discrete frequencies $f_1, f_2, \ldots, f_i$. In this way the transmitter antennas 2 and receiver antennas with corresponding impedance regulating devices 23, 83 are of very similar design.

In order to avoid direct coupling between the transmitter antenna 2 and the receiver antenna 8 cancelling devices 28 may be arranged for cancelling of direct waves or directly coupled signals between the transmitter antenna 2 and the receiver antenna 8. Differential coupling between receiver antennas 8, alternatively an attenuated differential coupling between a part of the voltage signal 25 to the transmitter antenna 2 and the receiver antenna 8 is one possible solution to cancel the emitted signal from the receiver antenna 8, particularly by emission of coherent continuous electromagnetic waves 26. By emission of pulsed signals cancellation of direct waves or direct coupled signals between the transmitter antenna 2 may be performed by means of delayed sampling at the receiver antenna 8 until the direct wave has passed. The control device 200 may be arranged preferably at the seabed or at the earth's surface, or at any other place.

The signal processing devices 82 for processing of the received signals $(85_1, 85_2, \ldots, 85_n)$ comprise circuits or means arranged for forming at least one discrete Fourier frequency spectrum of at least two of the parameters amplitude $A(\omega)$, phase $f(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$, with ω comprising essentially those frequencies $(f_1, f_2, \ldots, f_i)$ which were emitted from the transmitter antenna 2.

In an alternative embodiment the signal generator 22 may be arranged for generation of pulsed electrical signals 25 to the transmitter antenna 2 as in the known art.

The radar may be applied for detecting the gradient in resistivity represented by the OWC situated below the approximately horizontal well. Due to sedimentary processes the chemical and physical parameters (mineral composition, density, resistivity, permeability) along the deposited layers more constant than across the layers. Thus the

resistivity logs displayed in Fig. 4 from the vertical wells represent typical resistivity variations which may exist between the horizontal well and the OWC below the well.

In a producing vertical well the OWC will, due to the pressure and flow conditions, may form a vertical conical surface around the production well.

Water in such deep formations are usually more strongly electrically conductive, with resistivity below 1 Ωm.

The present invention is applied in a preferred embodiment inside the oil zone in the reservoir rock. The resistivity in the oil zone may be between 150 and 1000 Ωm. The transmitter antennas and the receiver antennas for the radar waves are arranged outside the metallic borehole string, which in a preferred embodiment is constituted by a production tube, but which in an alternative embodiment is constituted by a casing pipe, normally metallic. It is also possible to arrange the transmitter- and receiver antennas inside the casing pipe or production tubing if these pipes ar made of non-conductive materials, e.g. composite materials.

The tubing string 4 may comprise a production tubing or a casing, or equivalent. The receiver antennas 8 and the transmitter antenna 2 are arranged outside of the surface of the metallic parts of the tubing string 4. If the tubing string 4 is made of composite materials which do not comprise metal or other electrically conductive materials, the antennas 8 and 2 may be inside or inside the wall of the tubing string 4.

It is also possible to fix the antennas 2 and 8 in other ways than by cementing. The borehole radar with the antennas 2 and 8 may e.g. be retractable and arranged with a guiding slot/guide fin in order to be reinserted in exactly the same position and orientation in the production zone at a later point of time after the first radar detection.

In an alternative embodiment of the invention it is just likely applied in a vertical well. In Fig. 10b and 10c is illustrated how several pressure isolated producing formations are approached at each their water front, and how the different water fronts are monitored by means of the invention.

C l a i m s

1. Method detection by radar in a well (1) in a geological formation (9)

c h a r a c t e r i z e d i n

that it comprises the following steps:

i) arrangement of at least one transmitter antenna (2) in a fixed position and orientation in the well (1) relative to the geological formation (9);

ii) generation of a first series of electrical signals (25) to a transmitter antenna (2) and emission of a first series of electromagnetic waves (26_1) from the transmitter antenna (2) at a first point of time (t_1);

iii) reception of a first series of reflected electromagnetic waves ($85_1, 85_2, .., 85_n$) by at least one, preferably several receiver antennas ($8_1, 8_2, .., 8_n$), and transformation of the first series of reflected electromagnetic waves to preferably digital registrations (S_1);

iv) generation of a second series of electrical signals (25) to the transmitter antennas (2) and emission of a second series of electromagnetic waves (26_2) from the transmitter antenna (2), still in the same position and orientation in the well (1), at a later point of time (t_2), with the time difference t_2-t_1 typically being several hours, days or longer time;

v) reception of a second series of reflected electromagnetic waves ($85_1, 85_2, .., 85_n$) by the receiver antennas ($8_1, 8_2, .., 8_n$), and transformation of the second series of reflected electromagnetic waves to preferably digital registrations (S_2).

2. Method according to claim 1,

c h a r a c t e r i z e d i n t h a t

it additionally comprises the following steps:

vi) formation of a difference (D_{t2-t1}) by subtraction of the registrations (S_1) from the registrations (S_2);

vii) interpretation of the difference (D_{t2-t1}) with respect to distance and possibly a direction to a horizon with a change in electrical properties between the points of time (t_1) and (t_2).

3. Method according to claim 1,
c h a r a c t e r i z e d i n t h a t
the interpretation of the difference (D_{t2-t1}) is performed by searching for a resistivity changes which may represent a displacement of a liquid horizon, e.g. an oil/water contact OWC.

4. Method according to claim 1, 2 or 3,
c h a r a c t e r i z e d b y
emission of coherent continuous electromagnetic waves (26_1, 26_2) from the transmitter antenna (2).

5. Method according to claim 4,
c h a r a c t e r i z e d b y
emission of coherent continuous electromagnetic waves (26_1, 26_2) in steps, at a number of *i* different frequencies $f_1, f_2, \ldots, f_i$ from the transmitter antenna (2).

6. Method according to claim 4,
c h a r a c t e r i z e d b y
adjustment of impedance of the transmitter antenna (2) to each particular of the emitted discrete frequencies $f_1, f_2, \ldots, f_i$, for maximal power emission to the geophysical formation (9).

7. Method according to one of the above claims,
c h a r a c t e r i z e d i n
impedance adjustment of the receiver antennas (8) to each particular of the emitted discrete frequencies $f_1, f_2, \ldots, f_i$, for maximal reception of power from reflected electromagnetic waves from the geological formation (9).

8. Method according to one of the claims 1-7,
c h a r a c t e r i z e d b y
cancelling of direct waves or direct coupled signals between the transmitter antenna (2) and the receiver antenna (8) so that the direct wave interferes minimally with the r fl cted waves from the geological formation (9).

9. Method according to claim 8,

c h a r a c t e r i z e d b y
differential coupling between receiver antennas (8), or possibly a relative differential coupling between the signal from the receiver antenna (8) and a relatively attenuated part of the voltage signal (25) to the transmitter antenna (2).

10. Method according to claim 1,
c h a r a c t e r i z e d b y
processing of the received electromagnetic waves ($85_1, 85_2, .., 85_n$) or the registrations (S_1) or (S_2) in order to detect gradients in the electrical properties, preferably resistivity, in the geological formation (9).

11. Method according to claim 1,
c h a r a c t e r i z e d b y
processing of the received electromagnetic waves ($85_1, 85_2, .., 85_n$) or the registrations (S_1) or (S_2) in order to detect gradients in the electrical properties, preferably resistivity, in the geological formation (9) between two points of time (t_1) and (t_2).

12. Method according to one of the claims claim 1-11,
c h a r a c t e r i z e d b y
signal processing of time series representing the reflected signals ($85_1, 85_2, .., 85_n$) or the registrations (S_1) or (S_2) in order to form at least one discrete Fourier frequency spectrum of at least two of the parameters amplitude $A(\omega)$, phase $\phi(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$, with ω corresponding to the frequencies (f_1, f_2, ... , f_i) which were emitted from the transmitter antenna (2).

13. Method according to claim 5,
c h a r a c t e r i z e d b y
direct stepwise sampling of signals with amplitude $A(\omega)$, phase $\phi(\omega)$ of the electromagnetic waves ($85_1, 85_2, .., 85_n$) from the receiver antennas (8) in the frequency domain by the frequencies f_1, f_2, ... , f_i.

14. Method according to one of the claims 12 or 13, characterized by signal processing an inverse Fourier transform $F(\omega)->f(t)$ by inverse Fourier transforming at least two of the parameters amplitude $A(\omega)$, phase $\phi(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$, with ω comprising essentially the frequencies f_1, f_2, ... , f_i which were emitted from the transmitter antenna (2), and formation of a time series f(t) which may represent pseudo-reflexes formed by electromagnetic impedance gradients in the geological formation (9).

15. Method according to one of the previous claims, characterized by arrangement of a directionally sensitive antenna group (8') comprising three or more receiver antennas (8) about the tubing string's (4) axis and essentially by the same position along the tubing string (4), with the purpose to detect the electromagnetic waves (85_1,85_2,.., 85_n) and their reflectors' direction with respect to the tubing string's axis.

16. Method according to one of the previous claims, characterized by arrangement of a transmitter antenna group (2') comprising two or more transmitter antennas (2) about the tubing string' (2) axis and essentially by the same position along the tubing string (4), with the purpose of emitting electromagnetic waves (26) generally in a selected direction with respect to the tubing string's (4) axis.

17. Method according to one of the claims 1-3, characterized by generation of electrical signals (25) for emission of pulsed electromagnetic signals (26) from the transmitter antenna (2).

18. Device for detection of electrical properties in a geological formation (9) via a well (1), characterized by
(a) at least one transmitter antenna (2) for emission of

electromagnetic waves (26), arranged by a tubing string (4), with the transmitter antenna (2) being arranged for fixed mounting with respect to the geological formation (9);
(b) at least one, preferably more receiving antennas (8) for the reflected electromagnetic waves (26), by preferably the same tubing string (4), with the receiver antennas (8) being arranged for fixedly mounting with respect to the geological formation (9).

19. Device according to claim 8,
c h a r a c t e r i z e d b y
a directionally sensitive antenna group (8') comprising three or more receiving antennas (8) arranged about the tubing string's (4) axis and essentially by the same position along the tubing string (4), arranged for detecting the reflected electromagnetic wave's (26) and their reflectors' direction with respect to the tubing string's (4) axis.

20. Device according to claim 18 or 19,
c h a r a c t e r i z e d b y
a transmitter antenna group (2') comprising two or more transmitter antennas (2) arranged about the tubing string's (4) axis and essentially by the same position along the tubing string (4), arranged for emitting electromagnetic waves generally in a selected direction with respect to the tubing string's (4) axis.

21. Device according to claim 18, 19 or 20,
c h a r a c t e r i z e d b y
a tubing string antenna module (4'), arranged for fixed arrangement in a well (1), comprising

a transmitter antenna group (2') with at least two transmitter antennas (2) arranged by a first position along the tubing string antenna module (4'), and

at least one directionally sensitive group (8') with at least three receiver antennas (8) arranged by a second position along the tubing string antenna module (4').

22. Device according to claim 21,
c h a r a c t e r i z e d i n t h a t

the tubing string antenna module (4') comprises

a transmitter antenna group (2') with preferably two dipole transmitter antennas (2) arranged on either side of the tubing string module (4') by a first position along the tubing string module (4'),

a first directionally sensitive group (8') with preferably four dipole receiver antennas (8) arranged with even angular separation about the tubing string antenna module (4') by a second position along the tubing string antenna module (4'),

a second directionally sensitive group (8') with preferably four dipole receiver antennas (8) arranged with even angular separation about the tubing string antenna module (4') by a third position along the tubing string antenna module (4'), preferably at the opposite side of the transmitter antenna group (2') with respect to the first directionally sensitive group (8').

23. Device according to one of the above claims 18-22,
c h a r a c t e r i z e d b y
an electronics package (20) comprising:

a signal generator (22) for generation of electrical signals (25) to the transmitter antenna (2),

devices (80) for reception of signals ($85_1, 85_2, .., 85_n$) induced in each of the receiver antennas ($8_1, 8_2, .., 8_n$),

signal processing devices (82) for processing the received signals ($85_1, 85_2, .., 85_n$),

communication devices (82) for transmission of signals (105) representing the electrical signals ($85_1, 85_2, .., 85_n$), and for reception of control signals (205).

24. Device according to one of the claims 18-23,
c h a r a c t e r i z e d i n t h a t
the signal generator (22) for generating of electrical signals (25) to the transmitter antenna (2) is arranged for generation of coherent continuous electromagnetic waves (26) from the transmitter antenna (2).

25. Device according to claim 24,
c h a r a c t e r i z e d i n t h a t

the signal generator (22) for generating of electrical signals (25) to the transmitter antenna for emission of coherent continuous electromagnetic waves by a number of *i* different frequencies (f_1, f_2, ..., f_i) from the transmitter antenna (2).

26. Device according to one of the previous claims 18-25, characterized by an impedance adjustment device (23) arranged for adapting the transmitter antenna's (2) impedance to each particular of the emitted discrete frequencies (f_1, f_2, ..., f_i), for maximal power emission to the geological formation (9).

27. Device according to one of the previous claims 18-26, characterized by impedance adjustment devices (83) arranged for adapting the receiver antenna's ($8_1, 8_2, .., 8_n$) impedance for each particular of the emitted discrete frequencies (f_1, f_2, ..., f_i) for maximally effective reception of electromagnetic waves ($85_1, 85_2, .., 85_n$).

28. Device according to claim 18, characterized by cancelling devices (28) arranged for cancelling of direct waves or directly coupled signals between the transmitter antenna (2) and the receiver antenna (8).

29. Device according to claim 28, characterized by differential coupling between receiver antennas (8), possibly differential coupling between the transmitter antenna (2) and the receiver antenna (8).

30. Device according to claim 23, characterized in that the electronics package (20) is situated immediately near the antennas (2, 8).

31. Device according to claim 22 and 30, characterized in that

the tubing string antenna module (4') comprises the electronics package (20).

32. Device according to claim 30 or 31,
c h a r a c t e r i z e d   i n   t h a t
the electronics package (20) additionally comprises an address unit (55), an accumulator- and charging unit (56), a memory (54) and a rest mode unit (57).

33. Device according to one of the previous claims,
c h a r a c t e r i z e d   b y
a preferably electrical energy supply and communication line (7) arranged between the communication unit (100) in the electronics package (20) and control device (200).

34. Device according to one of the previous claims,
c h a r a c t e r i z e d   i n   t h a t
the control device (200) is situated by the sea bottom or the earth's surface.

35. Device according to one of the previous claims,
c h a r a c t e r i z e d   i n   t h a t
the signal processing devices (82) for processing of the received signals ($85_1, 85_2, .., 85_n$), is arranged to form at least one discrete Fourier frequency spectrum of at least two of the parameters amplitude $A(\omega)$, phase $\phi(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$, with ω comprising essentially the frequencies ($f_1, f_2, \ldots, f_i$) which were emitted from the transmitter antenna (2).

36. Device according to claim 23,
c h a r a c t e r i z e d   i n   t h a t
the signal generator (22) generates pulsed electrical signals (25) to the transmitter antenna (2).

37. Device according to claim 28 and 34,
c h a r a c t e r i z e d   i n
cancelling of direct waves or direct coupled signals between the transmitter antenna (2) by means of delayed sampling by

the receiver antenna (8).

38. System for detection of electrical properties in a geological formation (9) via a well (1), characterized in that it comprises
(k) a signal generator (22) for generation of electrical signals (25); to
(l) at least one transmitter antenna (22) for emission of electromagnetic waves (26), fixedly arranged by a tubing string (4) with respect to the geological formation (9),
(m) at least one, preferably more receiver antennas (8) for the reflected electromagnetic waves (26), by preferably the same tubing string (4), with the receiver antennas (8) being fixedly mounted with respect to the geological formation (9).
(n) devices (80) for reception of signals (85_1, 85_2 ,.., 85_n) induced in each of the receiver antennas (8_1, 8_2 ,..., 8_n) due to gradient in the electrical properties i both rocks and fluids in the geological formations (9),
(o) signal processing devices (82) for processing of the received signals (85_1, 85_2 ,.., 85_n),
(p) communication devices (100, 200) for transmission of signals (105) representing the electrical signals (85_1, 85_2 ,..., 85_n), and for reception of control signals (205).

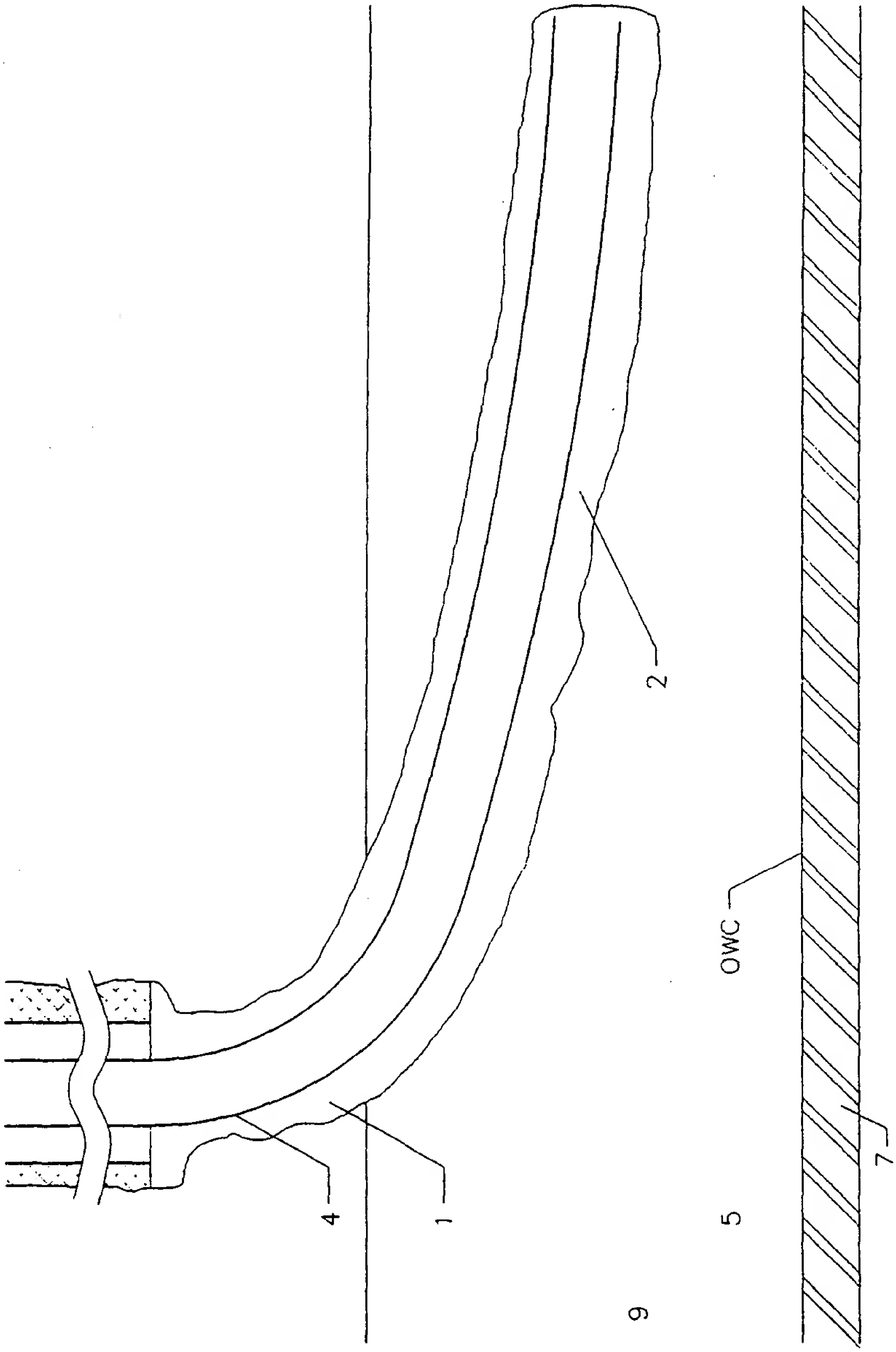


FIG. 1

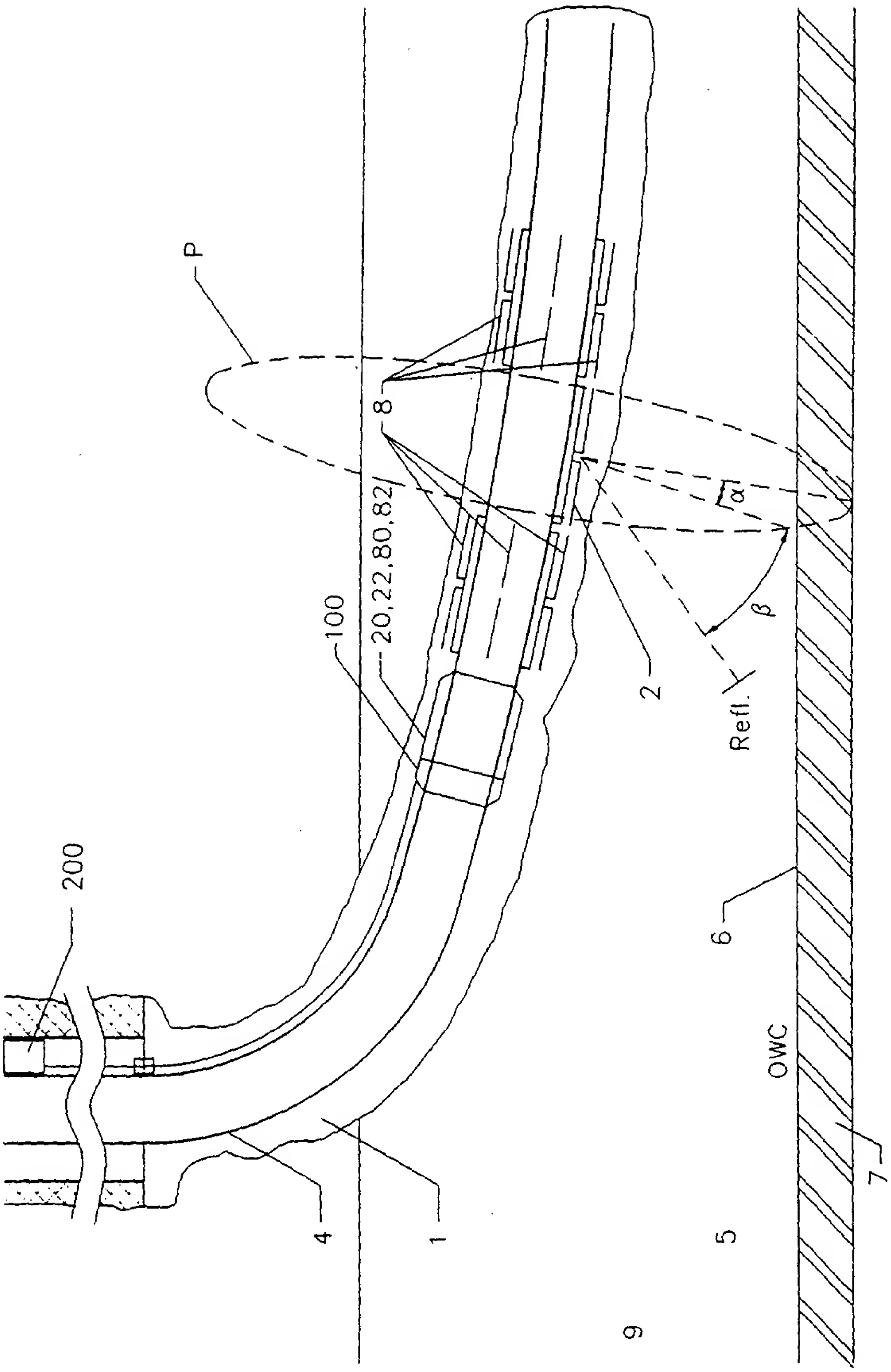
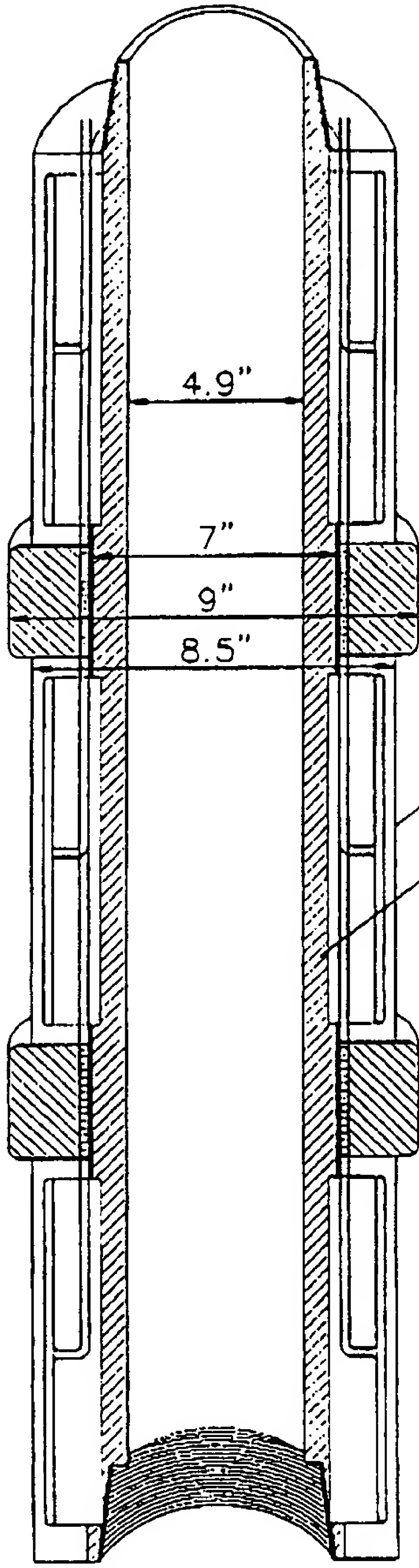


FIG. 2



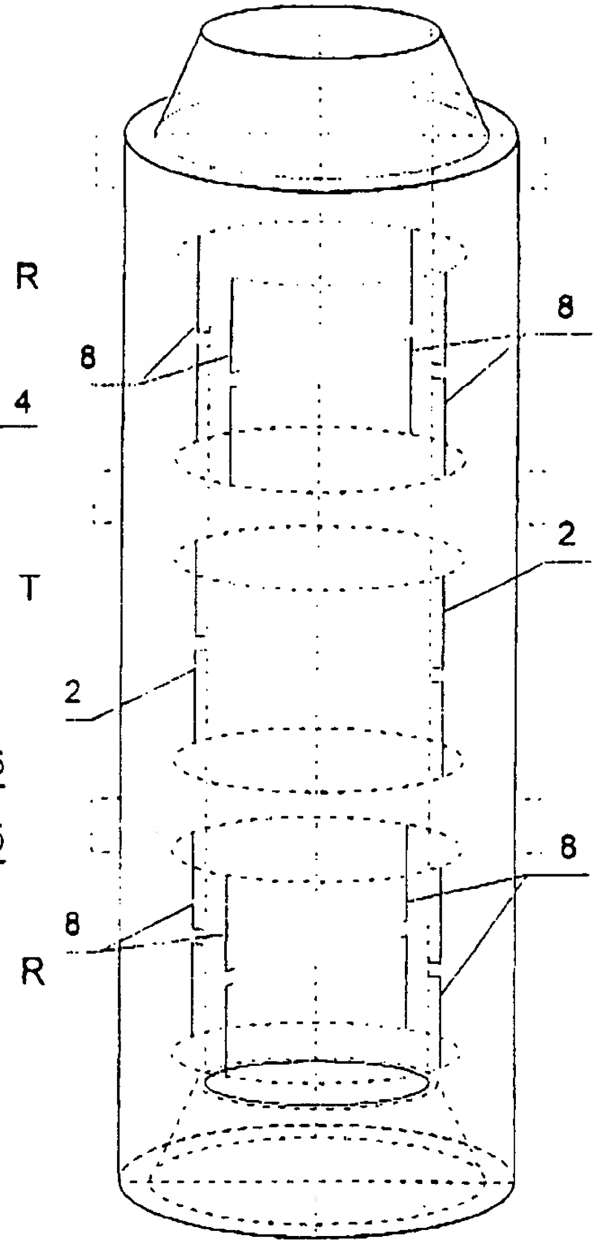


Fig. 2c

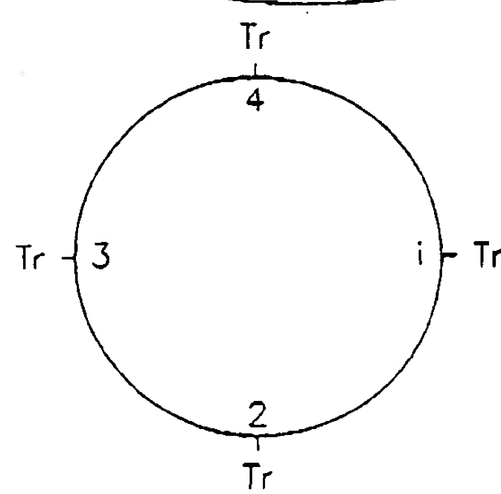


FIG. 2b

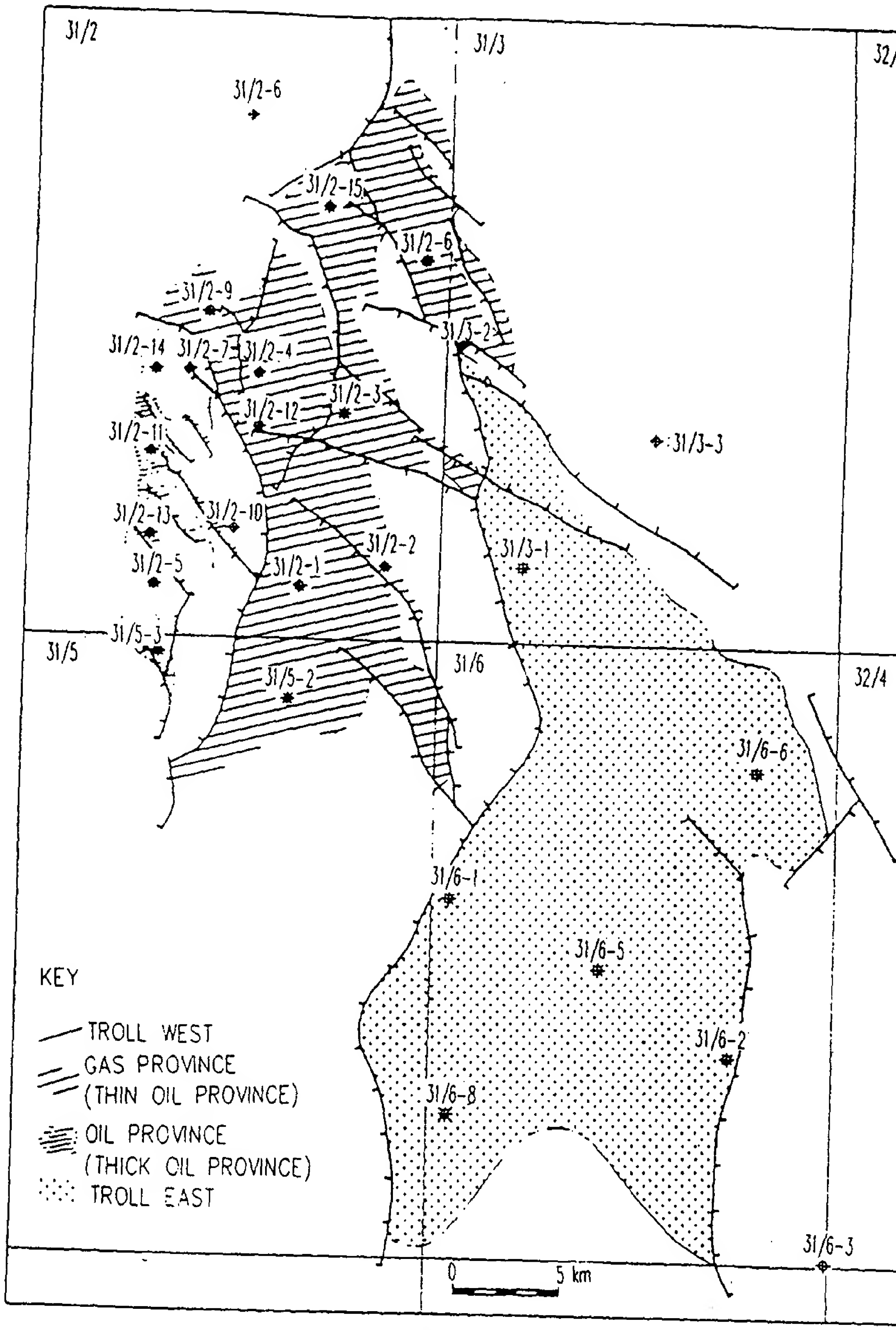

31/2
31/3
32/1
31/2-6
31/2-15
31/2-6
31/2-9
31/3-2
31/2-14
31/2-7
31/2-4
31/2-3
31/2-12
31/3-3
31/2-11
31/2-13
31/2-10
31/2-2
31/3-1
31/2-5
31/2-1
31/5-3
31/5
31/6
32/4
31/5-2
31/6-6
31/6-1
31/6-5
31/6-2
31/6-8
31/6-3
0
5 km
KEY
TROLL WEST
GAS PROVINCE
(THIN OIL PROVINCE)
OIL PROVINCE
(THICK OIL PROVINCE)
TROLL EAST

FIG. 3a

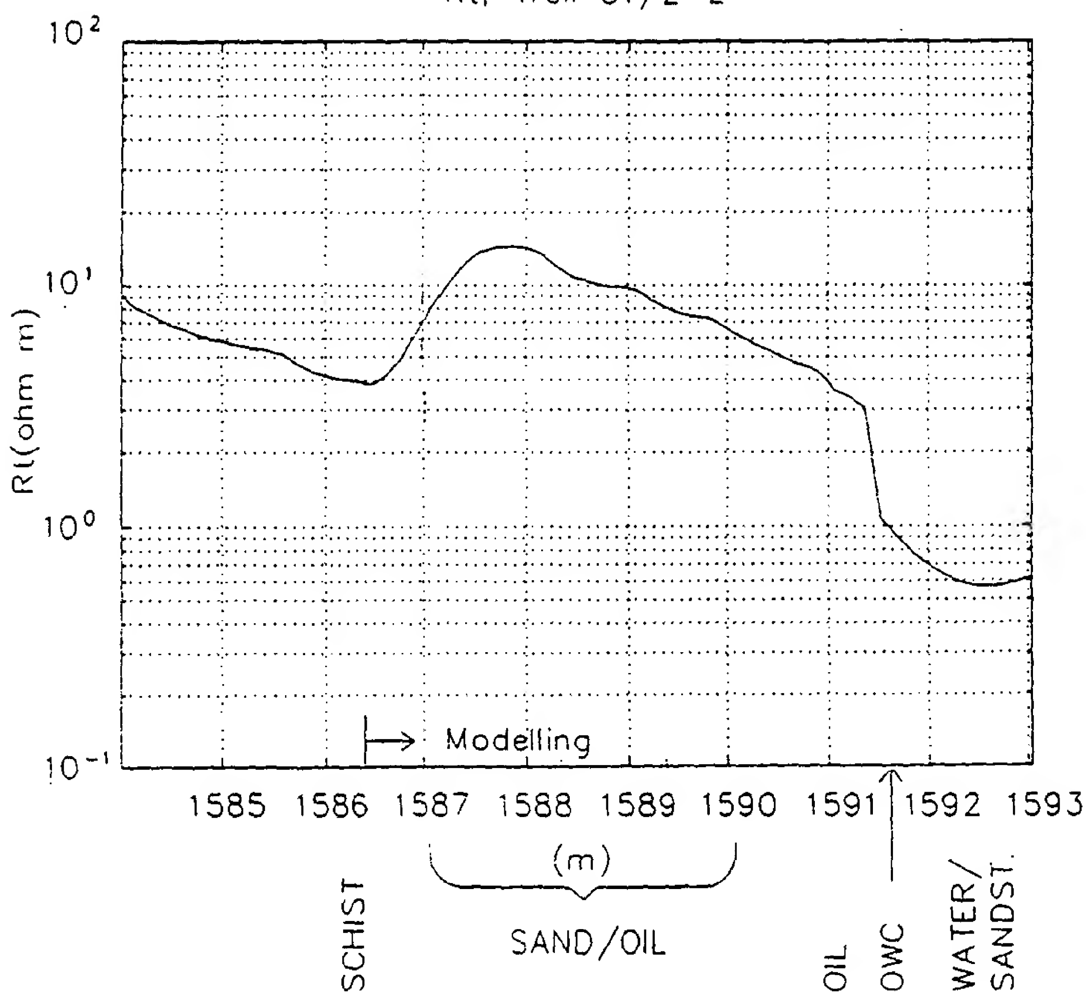

Rt, Troll 31/2-2
10^2
10^1
10^0
10^{-1}
Rt(ohm m)
Modelling
1585 1586 1587 1588 1589 1590 1591 1592 1593
(m)
SCHIST
SAND/OIL
OIL
OWC
WATER/SANDST.

FIG. 3b

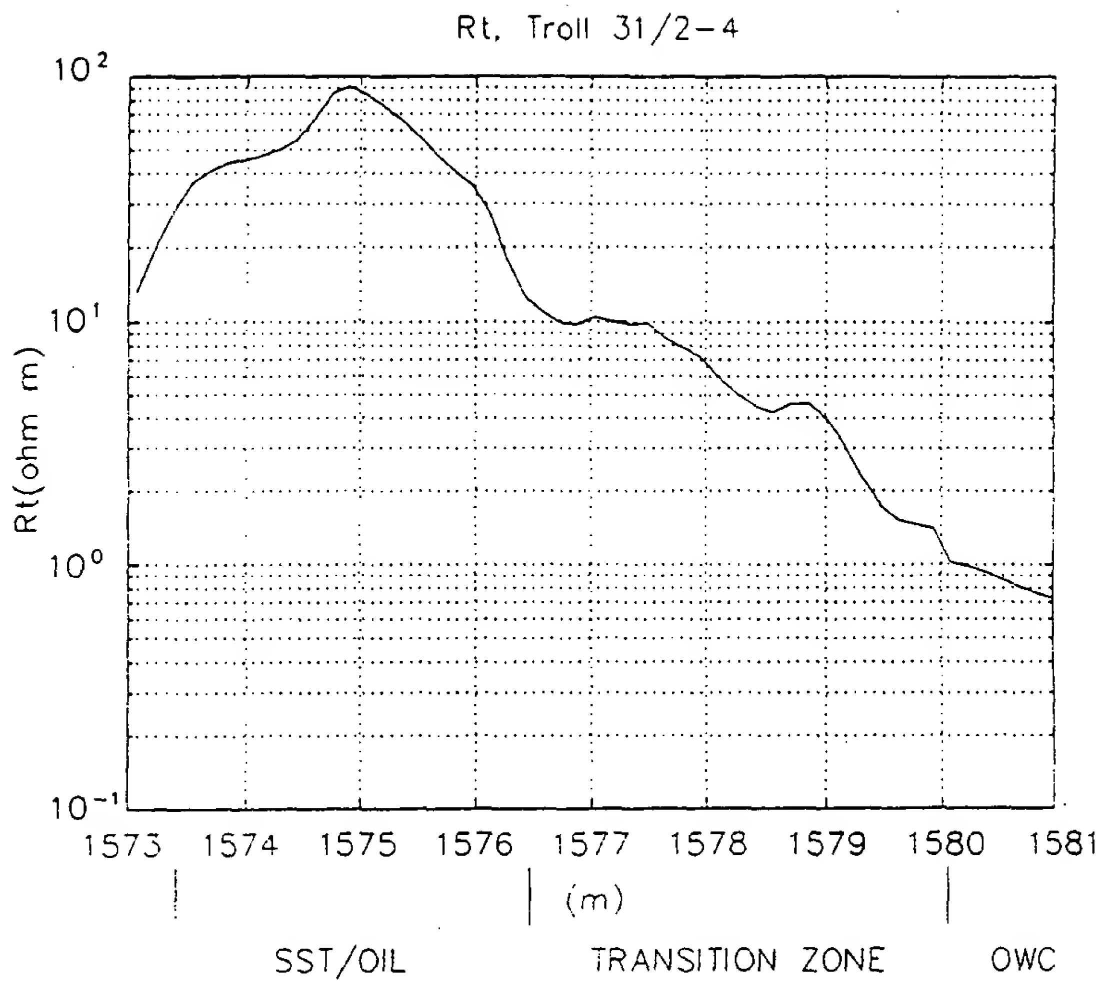

Rt, Troll 31/2-4
10²
10¹
10⁰
10⁻¹
Rt(ohm m)
1573
1574
1575
1576
1577
1578
1579
1580
1581
(m)
SST/OIL
TRANSITION ZONE
OWC

FIG. 3c

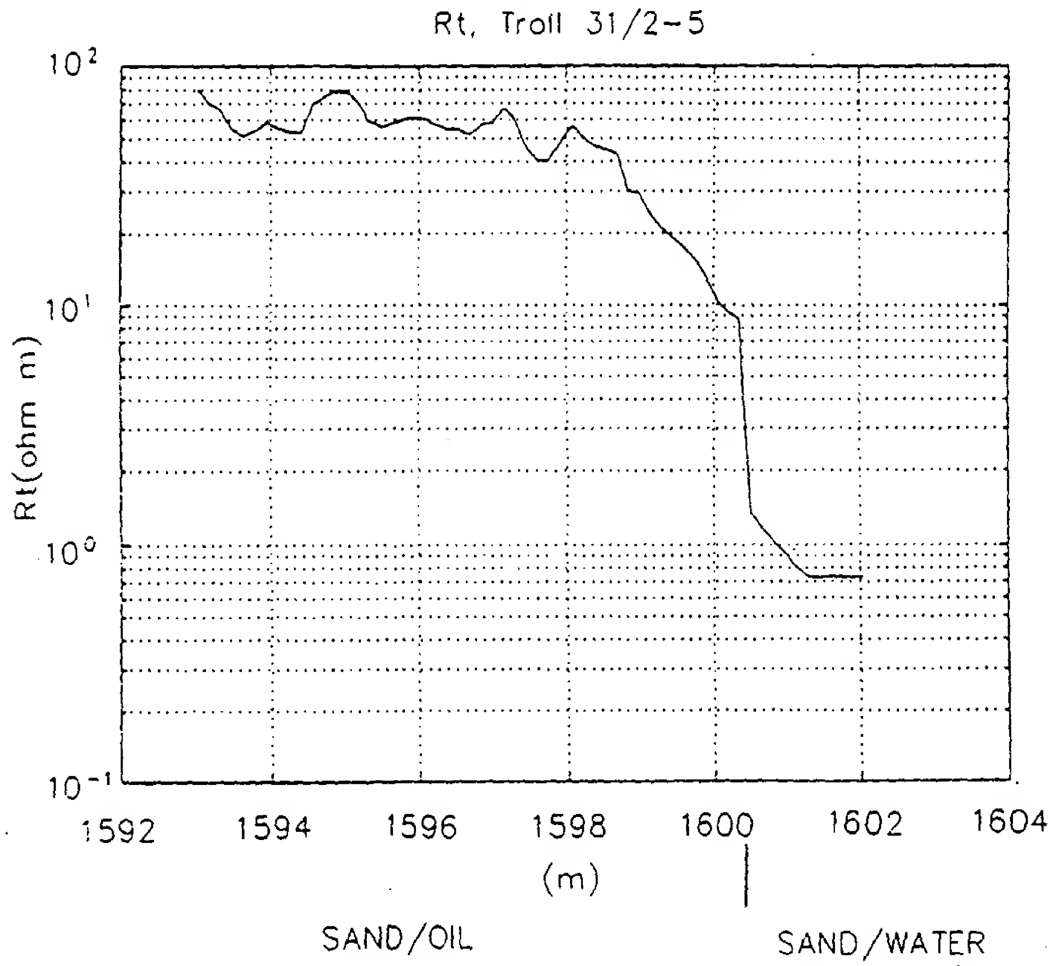

Rt, Troll 31/2-5
10^2
10^1
10^0
10^{-1}
Rt(ohm m)
1592
1594
1596
1598
1600
1602
1604
(m)
SAND/OIL
SAND/WATER

FIG. 3d

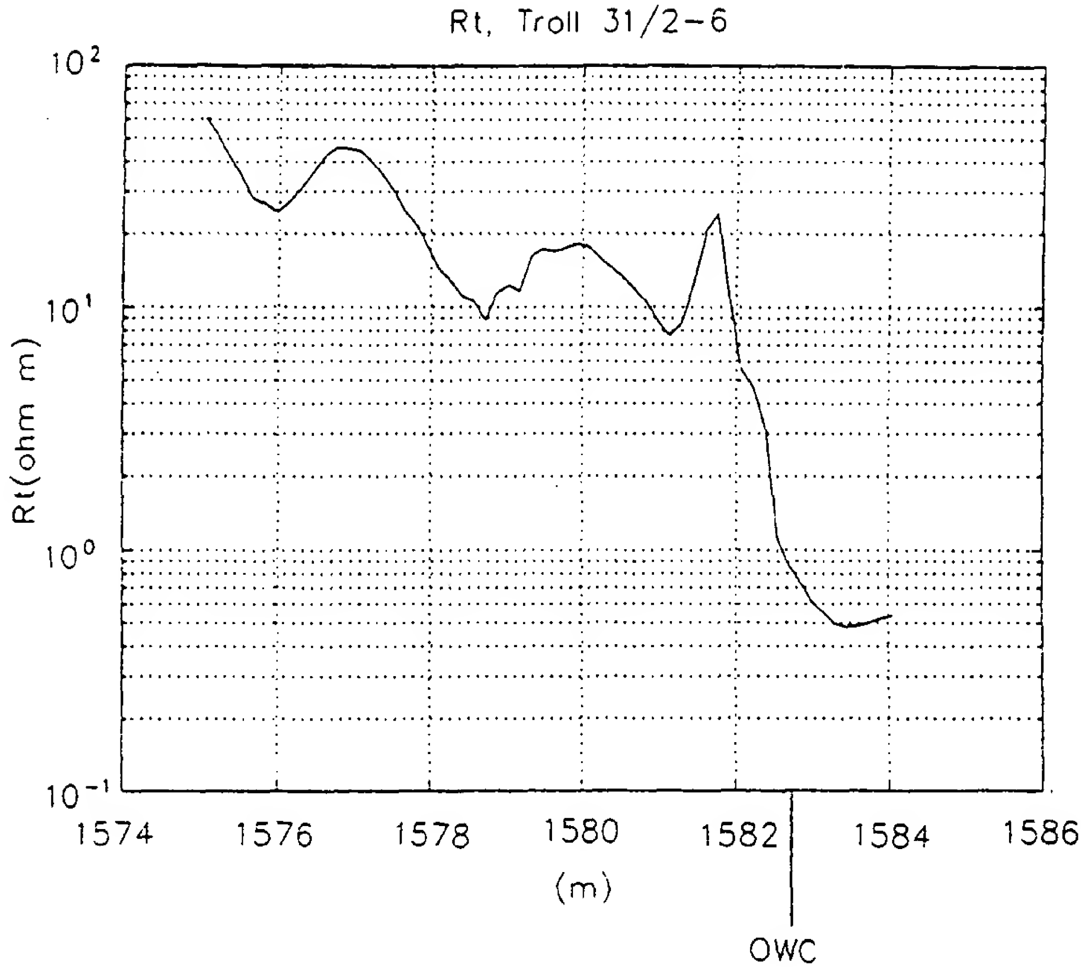

Rt, Troll 31/2-6
10^2
10^1
10^0
10^{-1}
Rt(ohm m)
1574
1576
1578
1580
1582
1584
1586
(m)
OWC

FIG. 3e

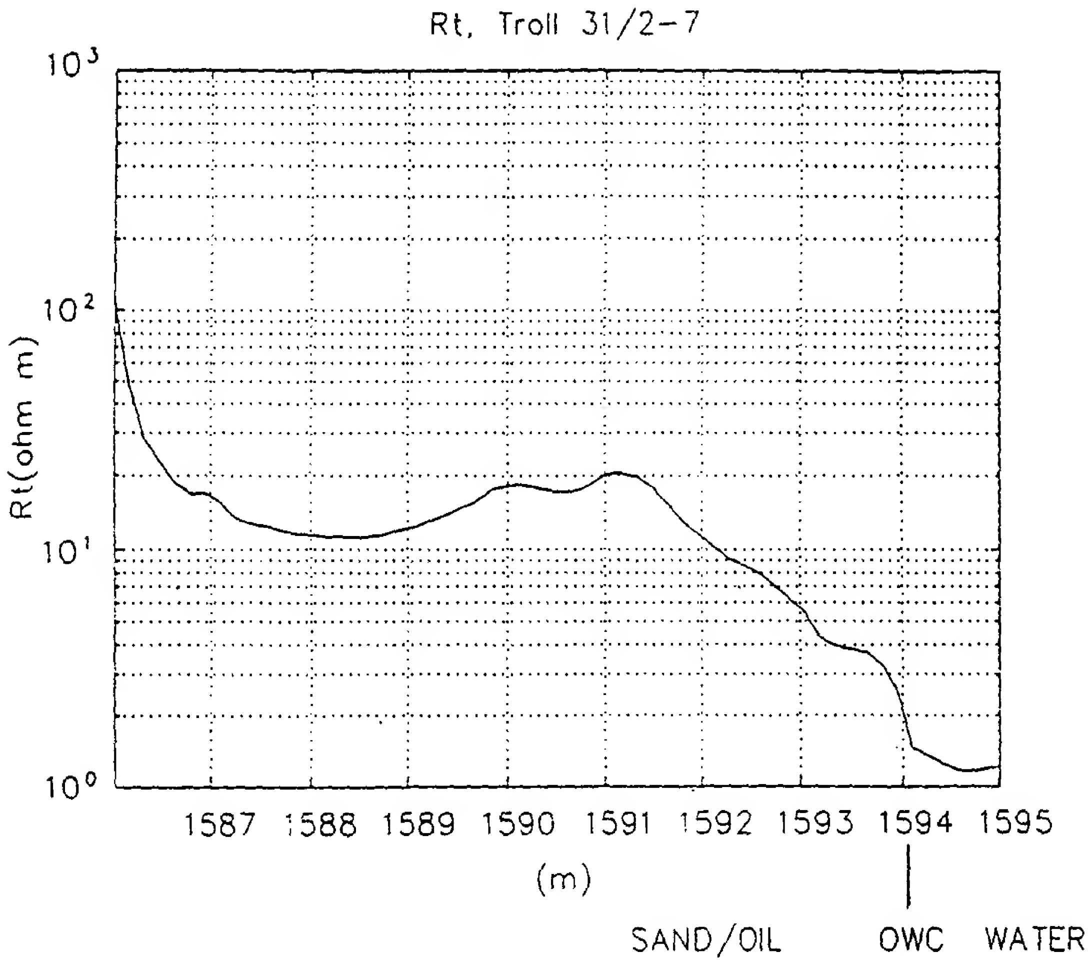

Rt, Troll 31/2-7
10^3
10^2
10^1
10^0
Rt(ohm m)
1587 1588 1589 1590 1591 1592 1593 1594 1595
(m)
SAND/OIL
OWC
WATER

FIG. 3f

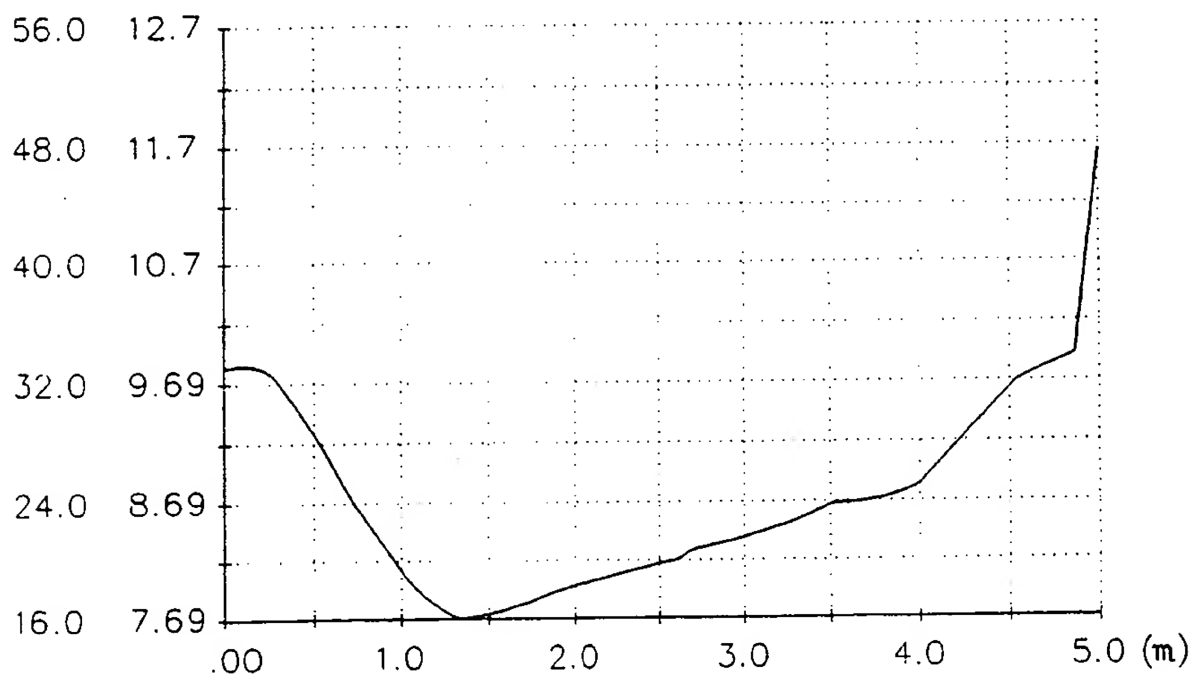


FIG. 4a

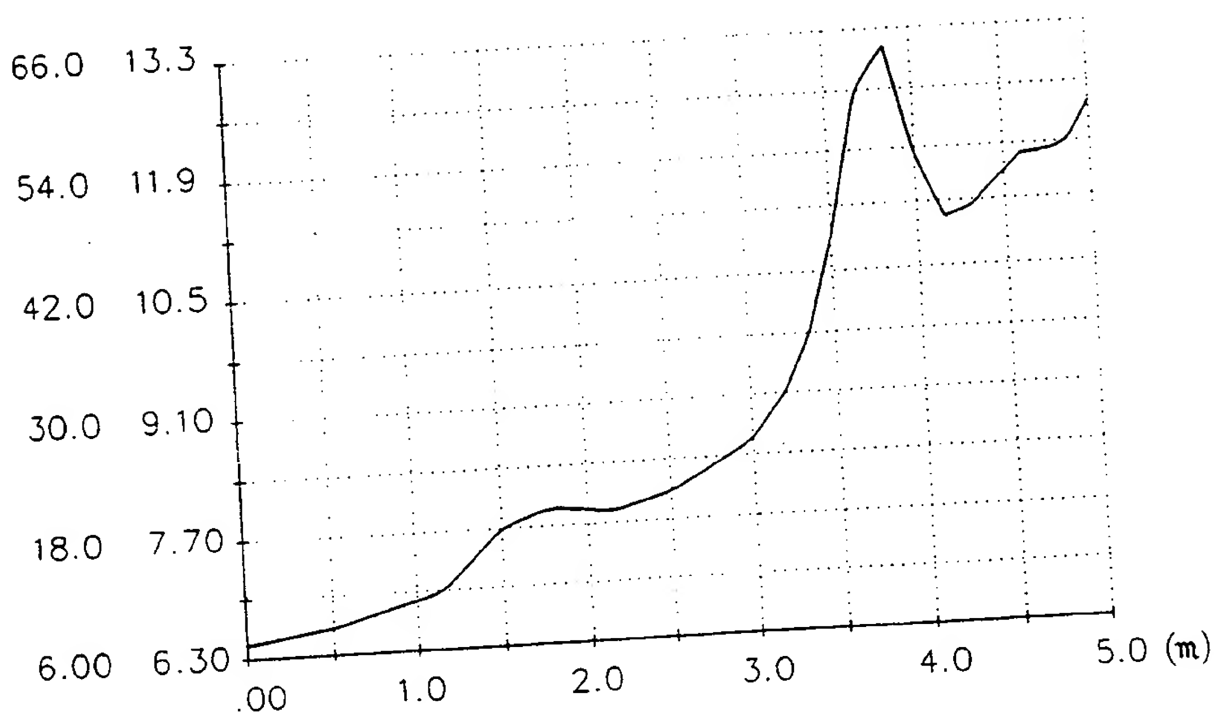


FIG. 4b

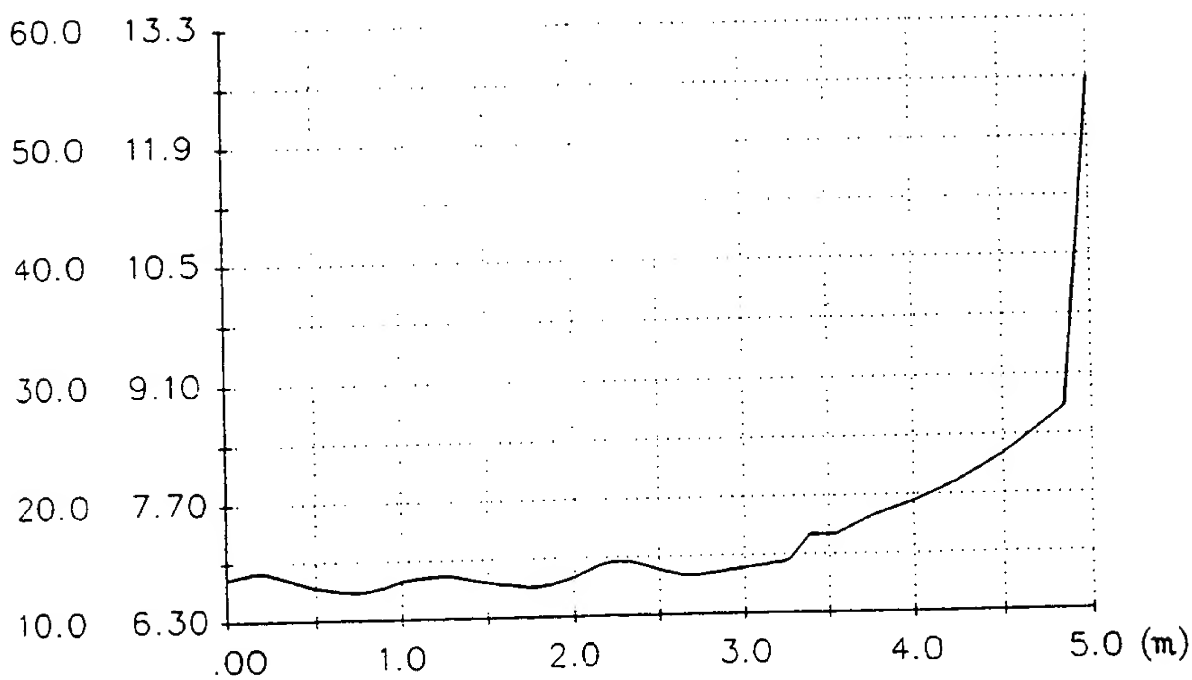


FIG. 4c

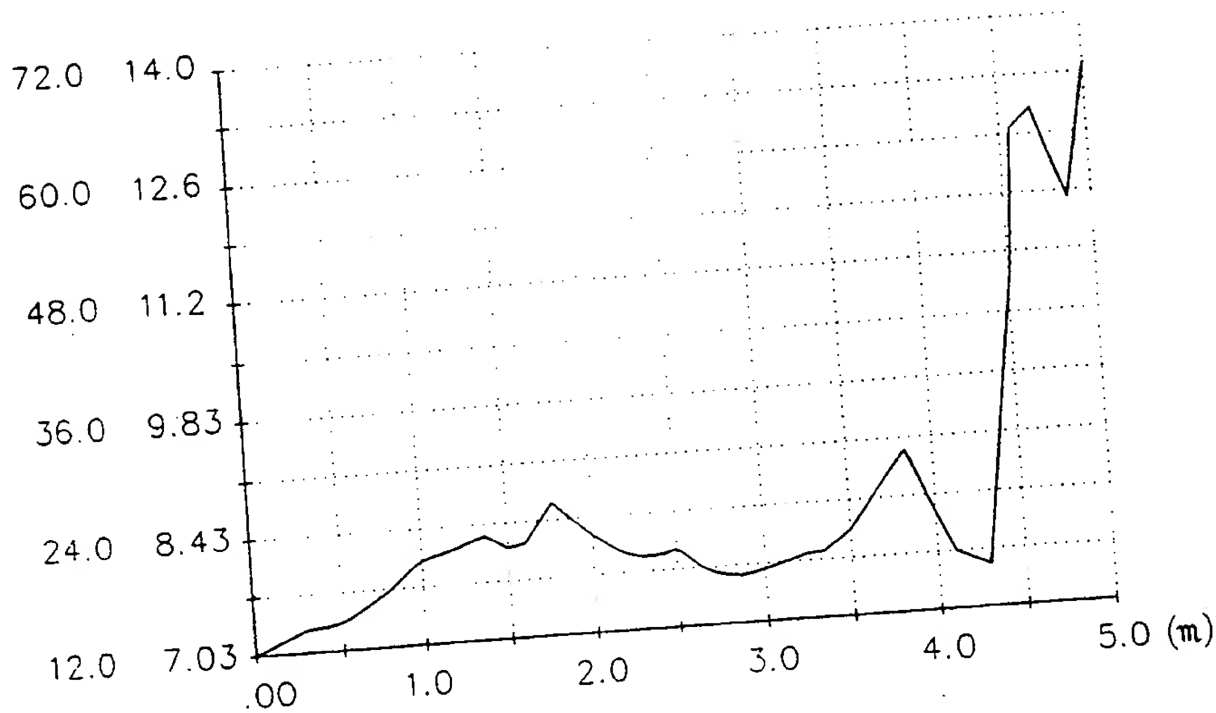


FIG. 4d

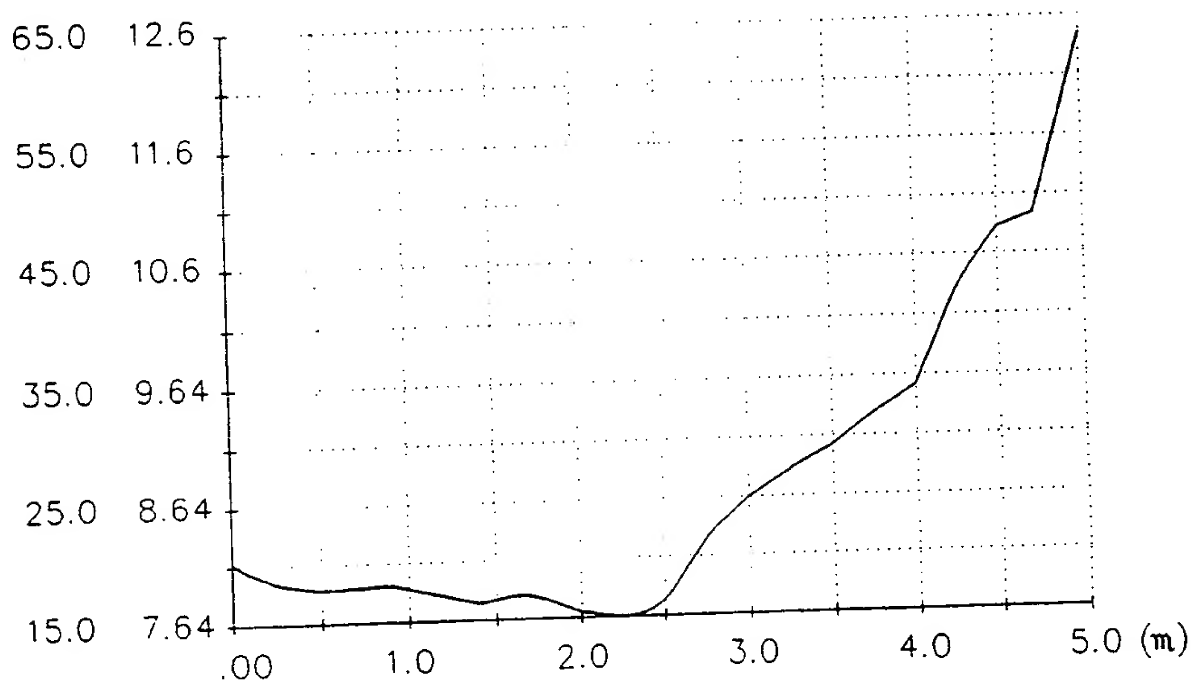


FIG. 4e

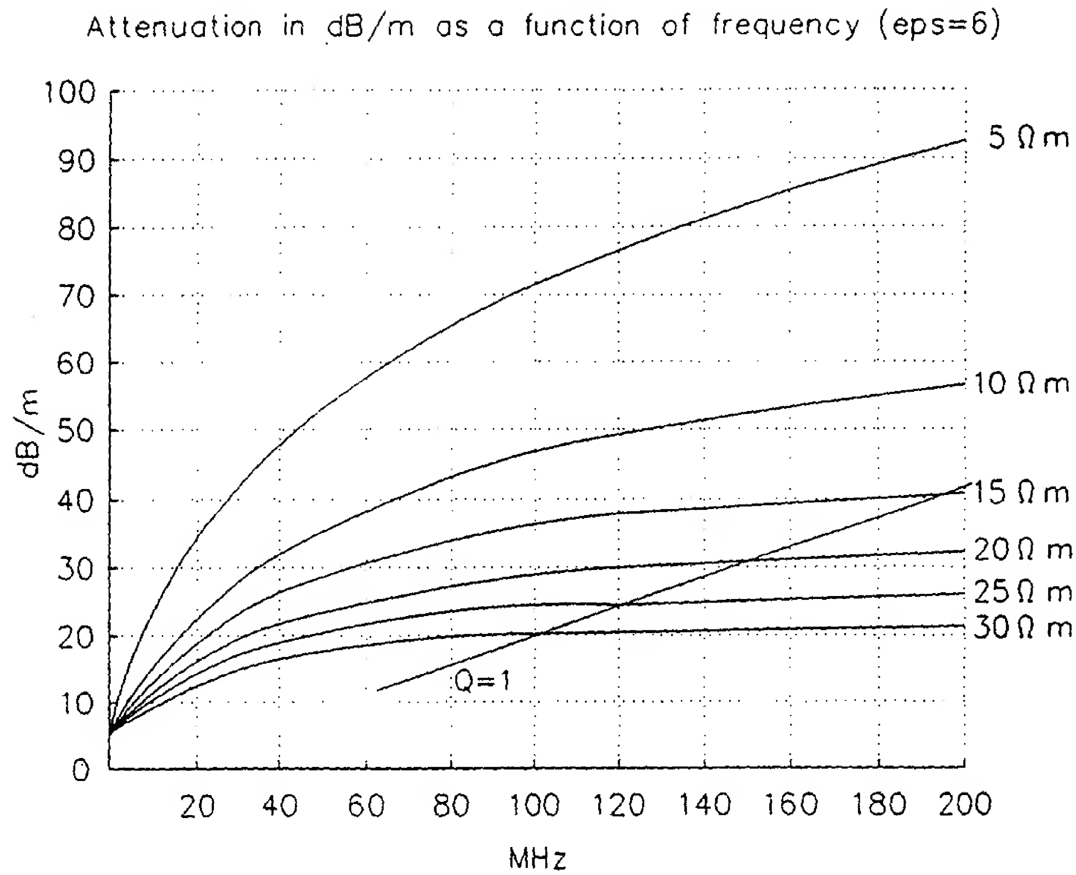

Attenuation in dB/m as a function of frequency (eps=6)
dB/m
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
MHz
5 Ω m
10 Ω m
15 Ω m
20 Ω m
25 Ω m
30 Ω m
Q=1

FIG. 5a

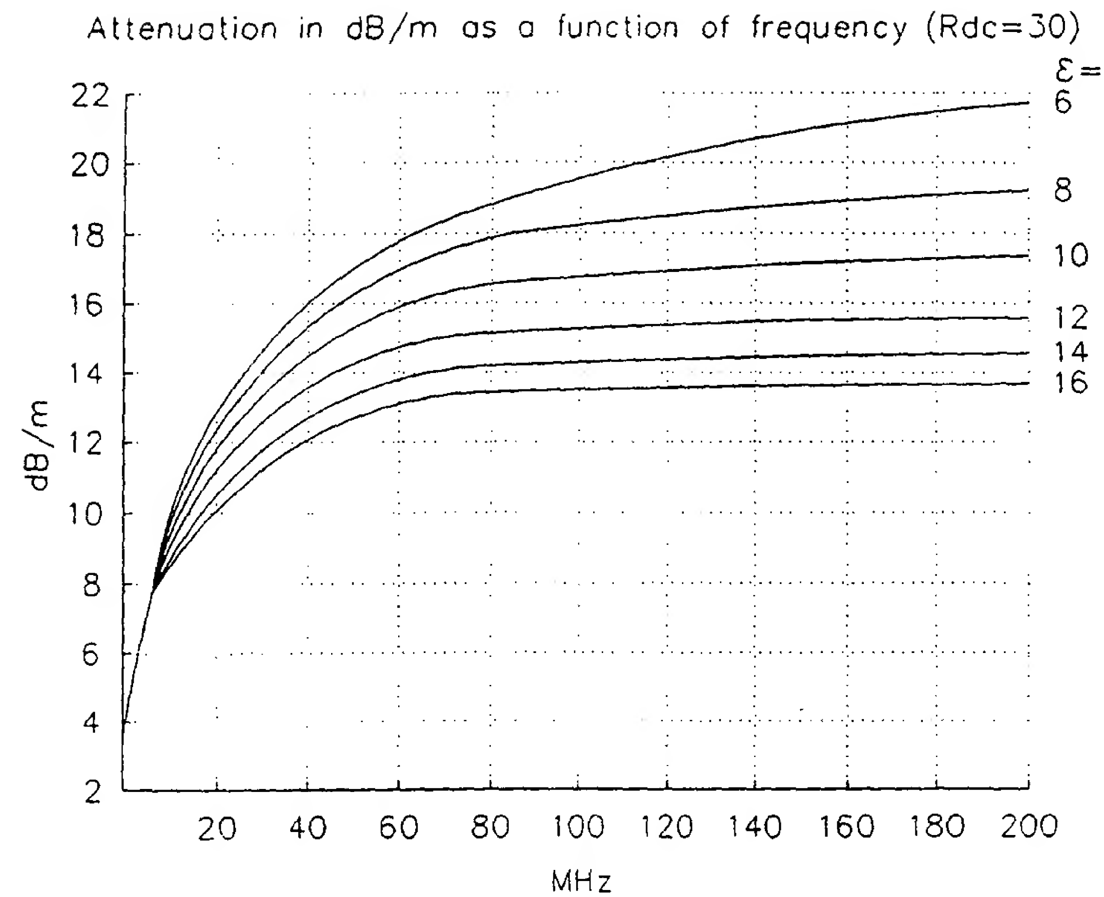

Attenuation in dB/m as a function of frequency (Rdc=30)
ε=
6
8
10
12
14
16
22
20
18
16
14
12
10
8
6
4
2
dB/m
20
40
60
80
100
120
140
160
180
200
MHz

FIG. 5b

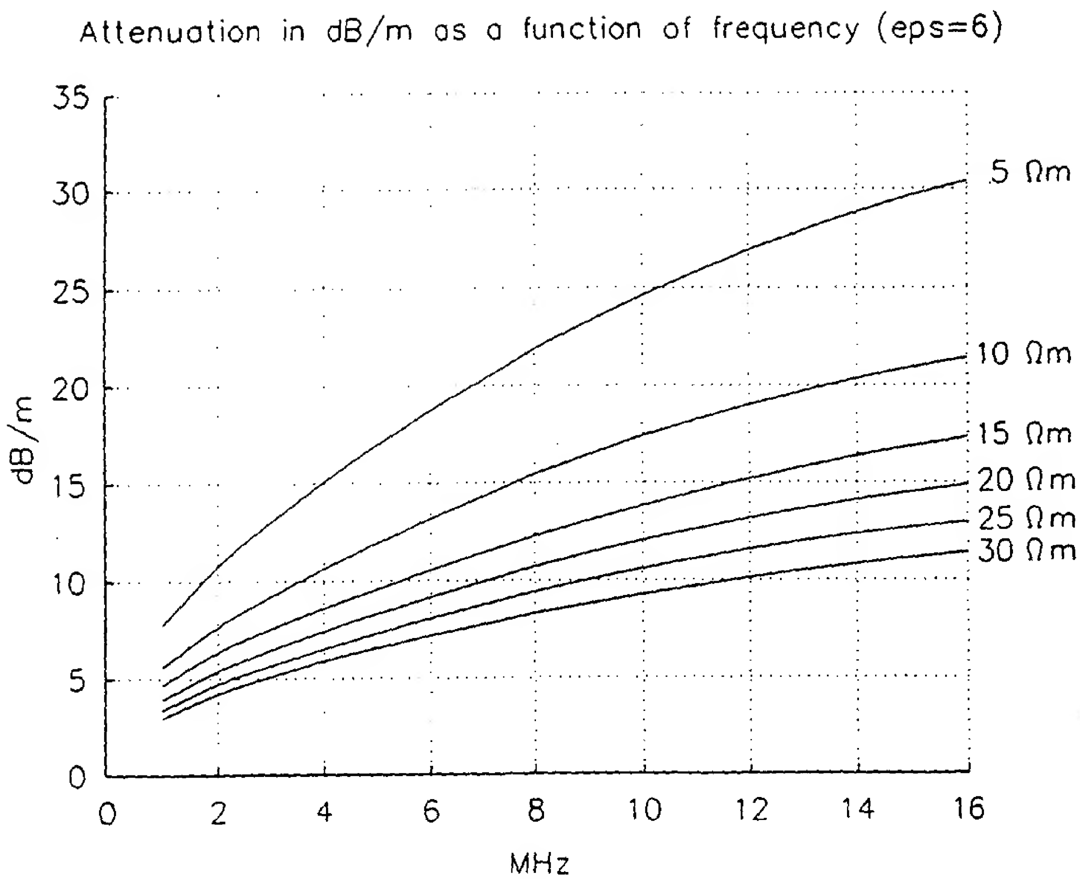

Attenuation in dB/m as a function of frequency (eps=6)
dB/m
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
MHz
5 Ωm
10 Ωm
15 Ωm
20 Ωm
25 Ωm
30 Ωm

FIG. 5c

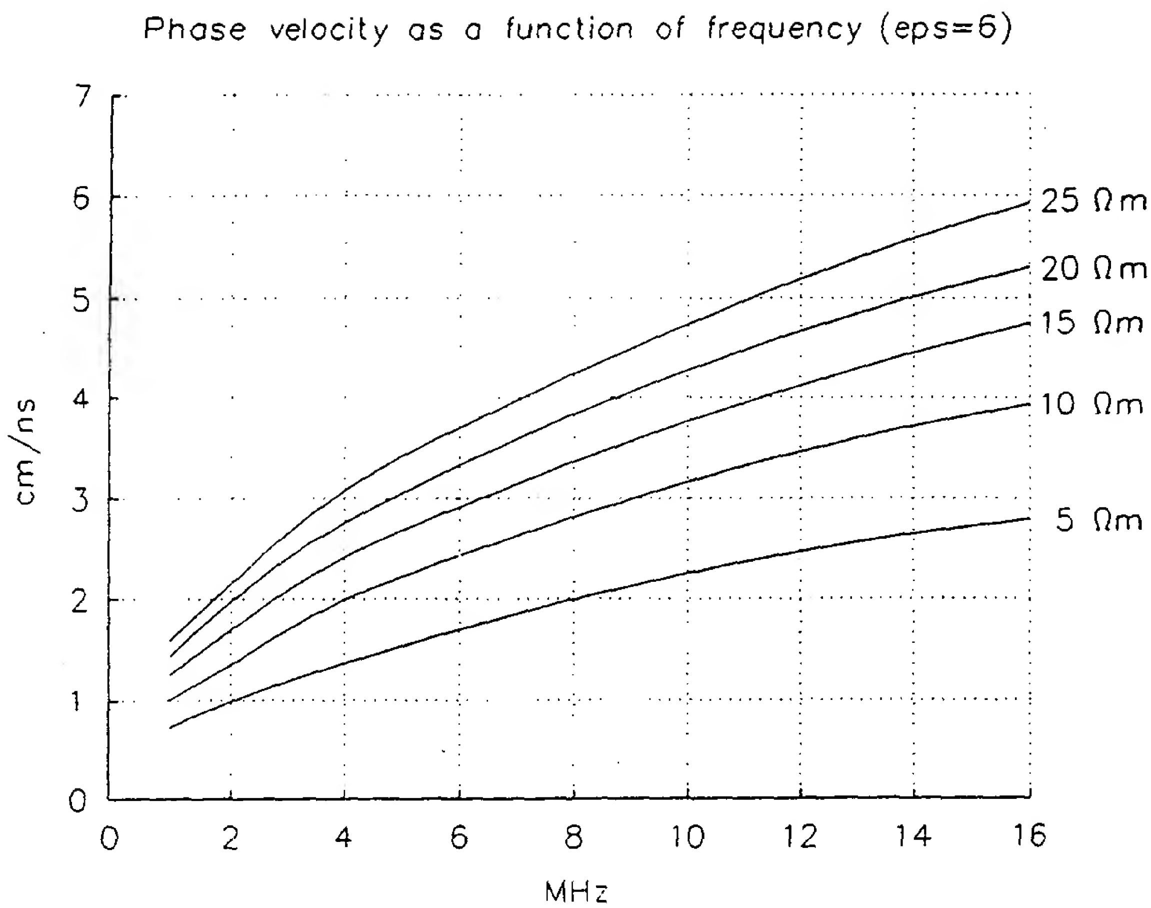

Phase velocity as a function of frequency (eps=6)
cm/ns
MHz
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
16
25 Ωm
20 Ωm
15 Ωm
10 Ωm
5 Ωm

FIG. 5d

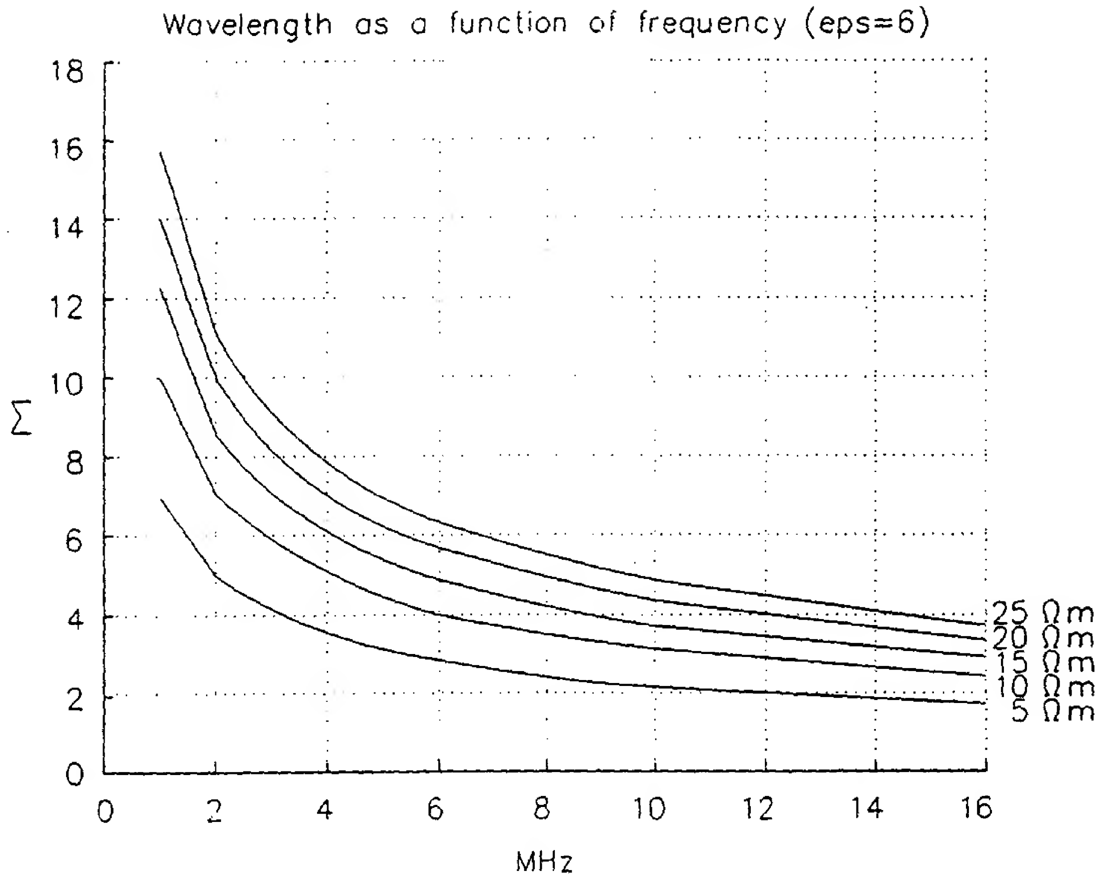

Wavelength as a function of frequency (eps=6)
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
MHz
25 Ωm
20 Ωm
15 Ωm
10 Ωm
5 Ωm

FIG. 5e

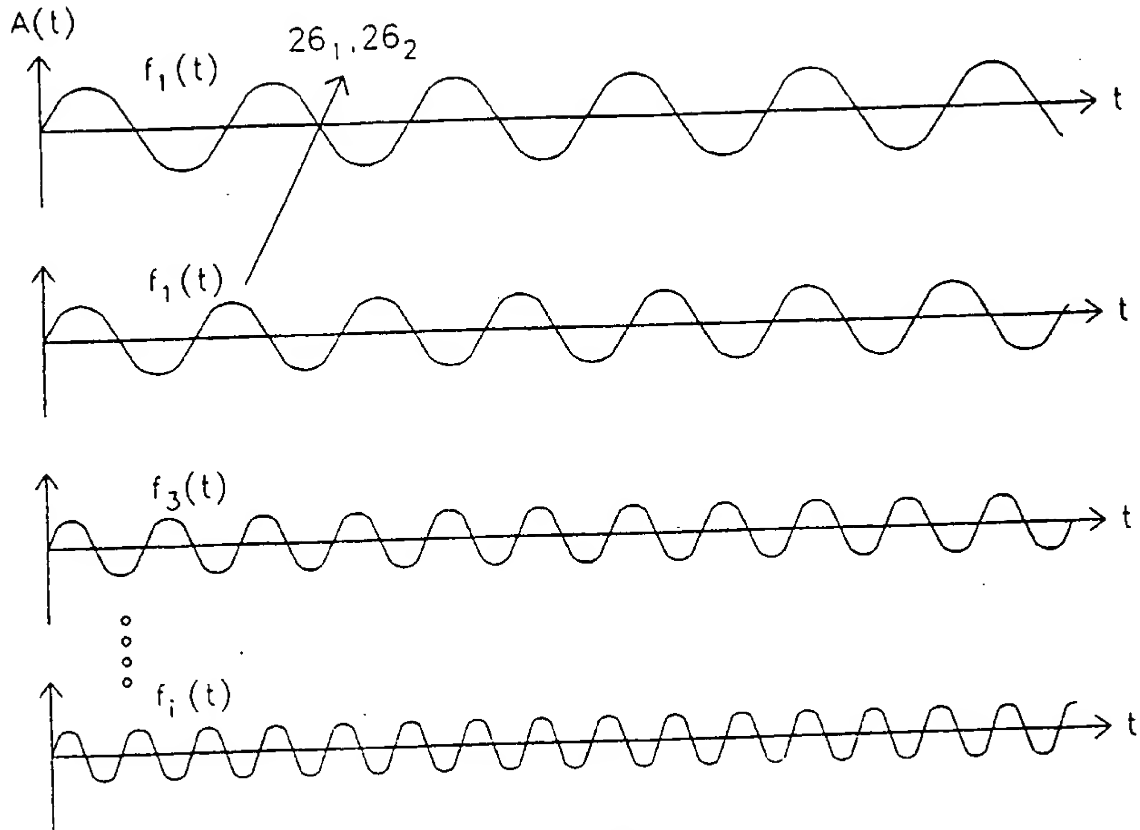

A(t)
$26_1, 26_2$
$f_1(t)$
t
$f_1(t)$
t
$f_3(t)$
t
$f_i(t)$
t

FIG. 6a

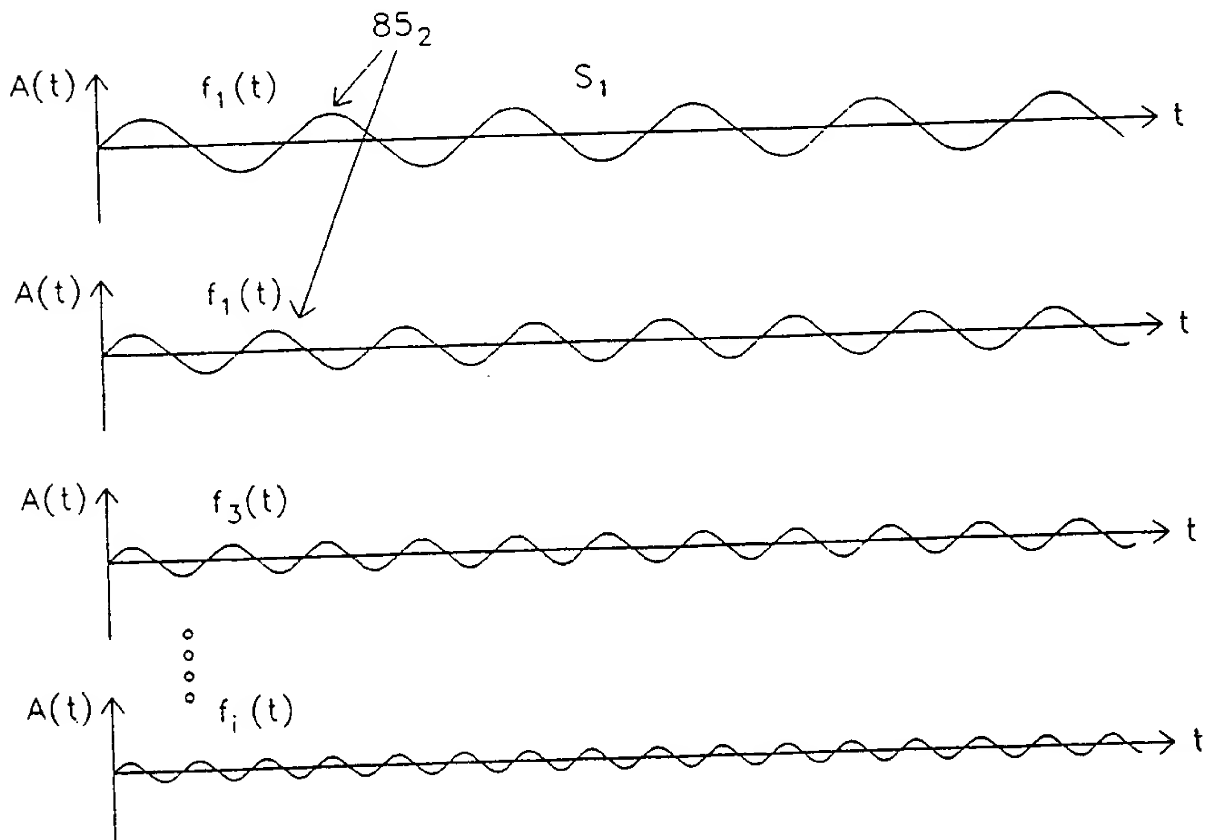

85_2
A(t)
$f_1(t)$
S_1
t
A(t)
$f_1(t)$
t
A(t)
$f_3(t)$
t
A(t)
$f_i(t)$
t

FIG. 6b

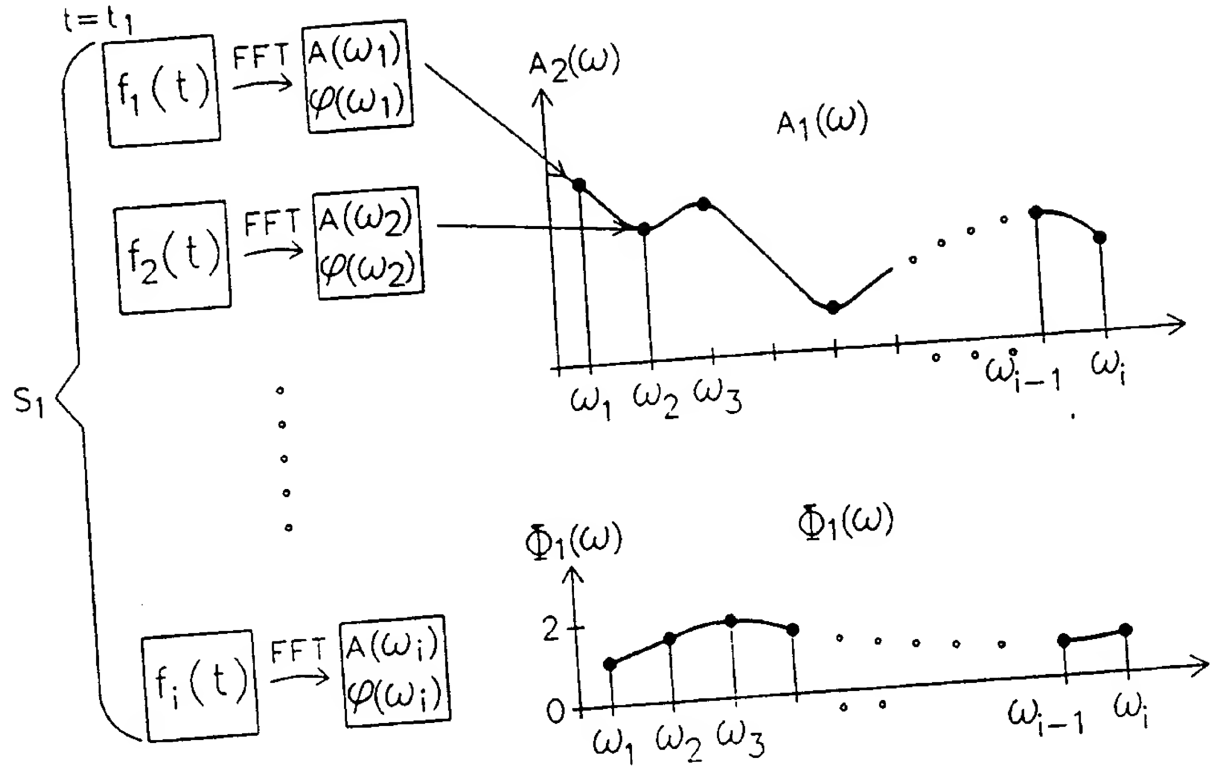

t=t1
f1(t)
FFT
A(ω1)
φ(ω1)
f2(t)
FFT
A(ω2)
φ(ω2)
S1
fi(t)
FFT
A(ωi)
φ(ωi)
A2(ω)
A1(ω)
ω1 ω2 ω3
ωi-1 ωi
Φ1(ω)
Φ1(ω)
2
0
ω1 ω2 ω3
ωi-1 ωi

FIG. 6c

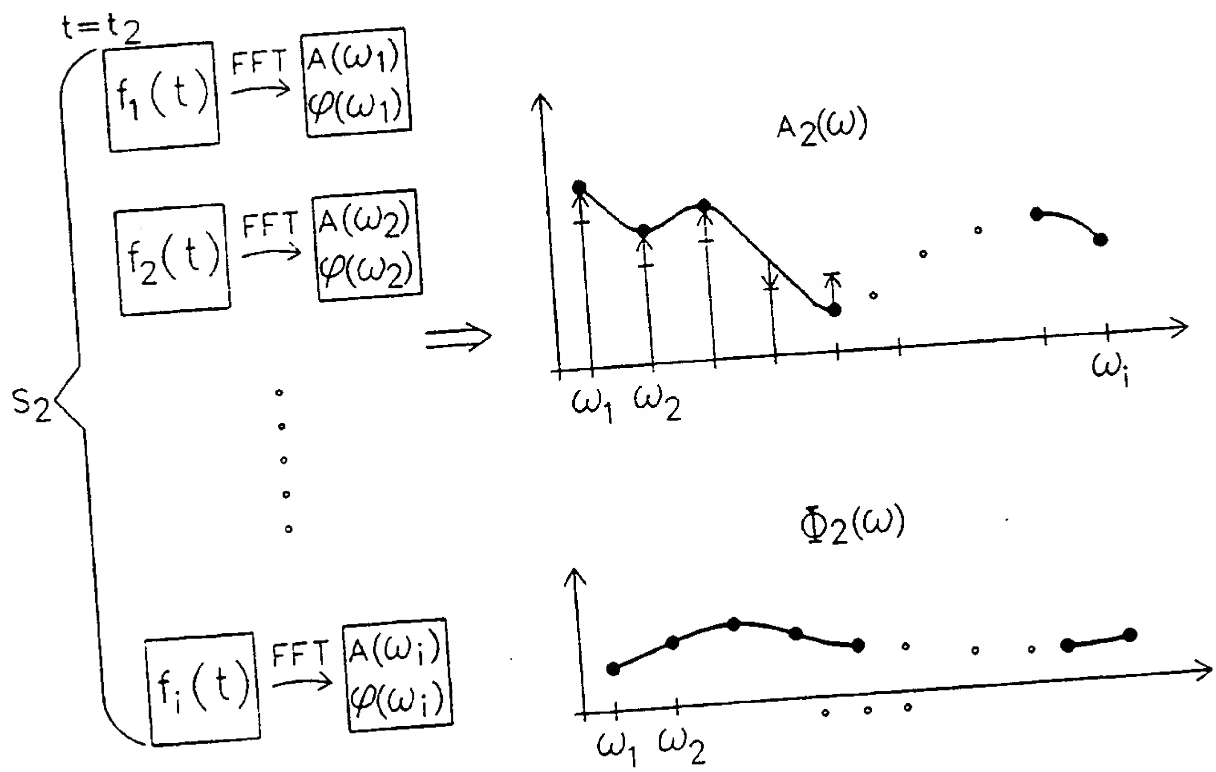

t=t2
f1(t)
FFT
A(ω1)
φ(ω1)
f2(t)
FFT
A(ω2)
φ(ω2)
S2
fi(t)
FFT
A(ωi)
φ(ωi)
A2(ω)
ω1 ω2
ωi
Φ2(ω)
ω1 ω2

FIG. 6d

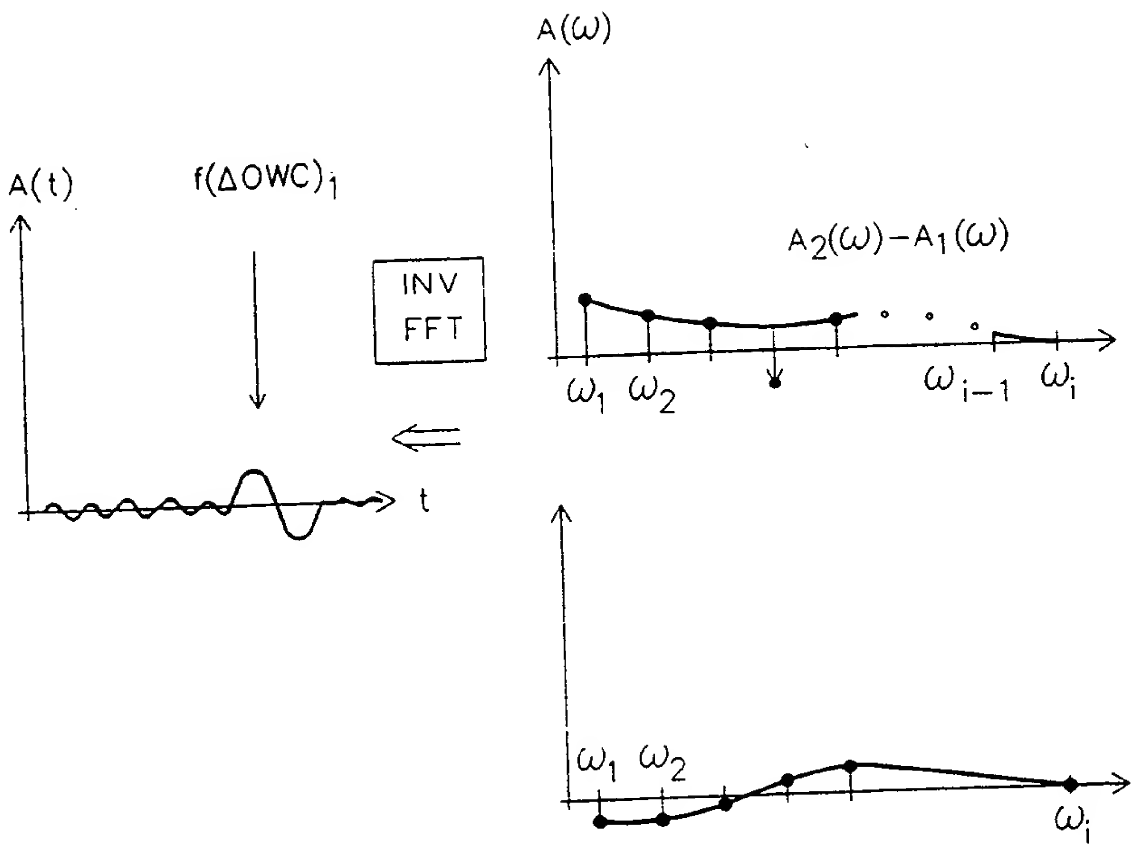


FIG. 6e

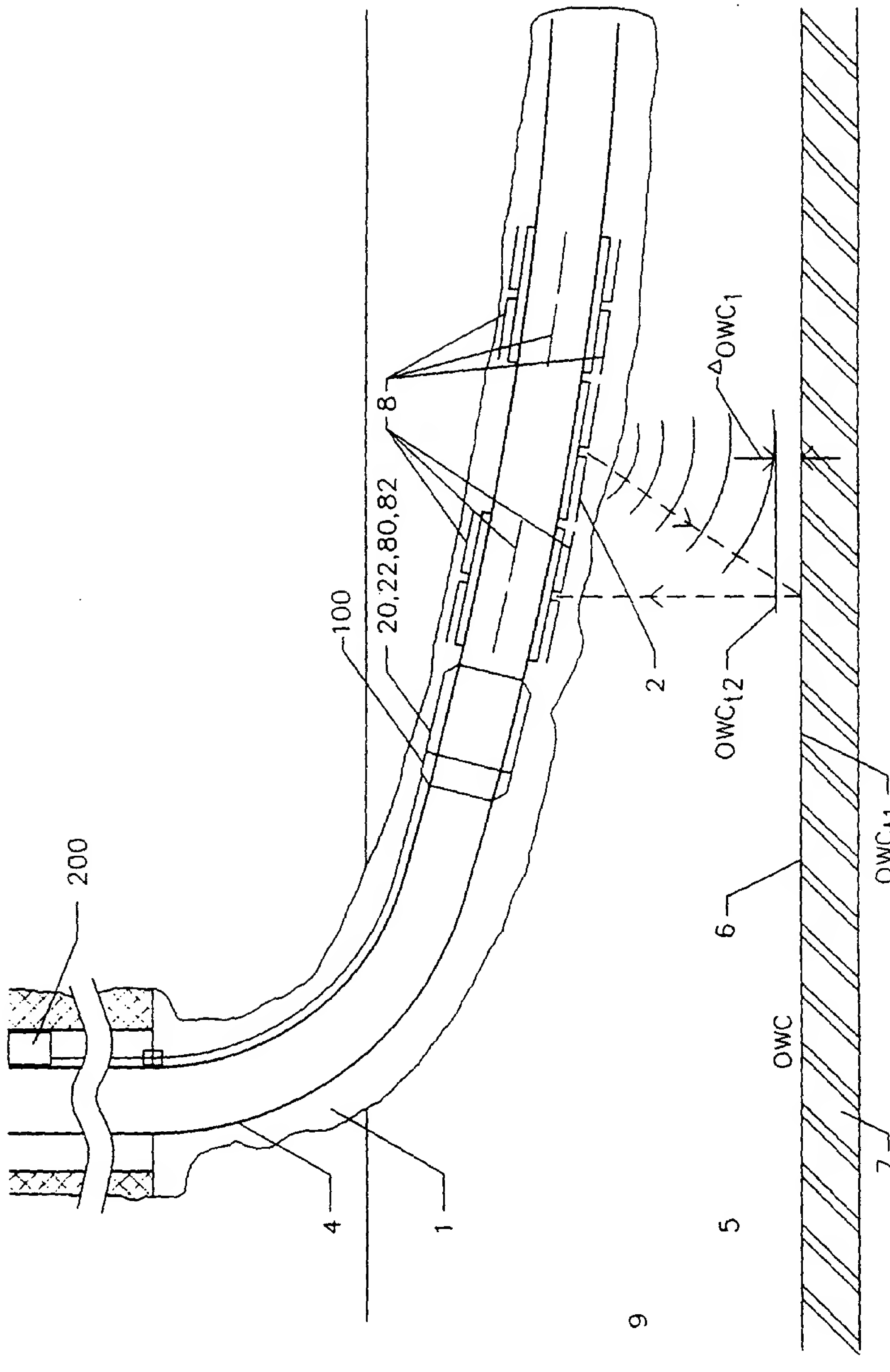


FIG. 7

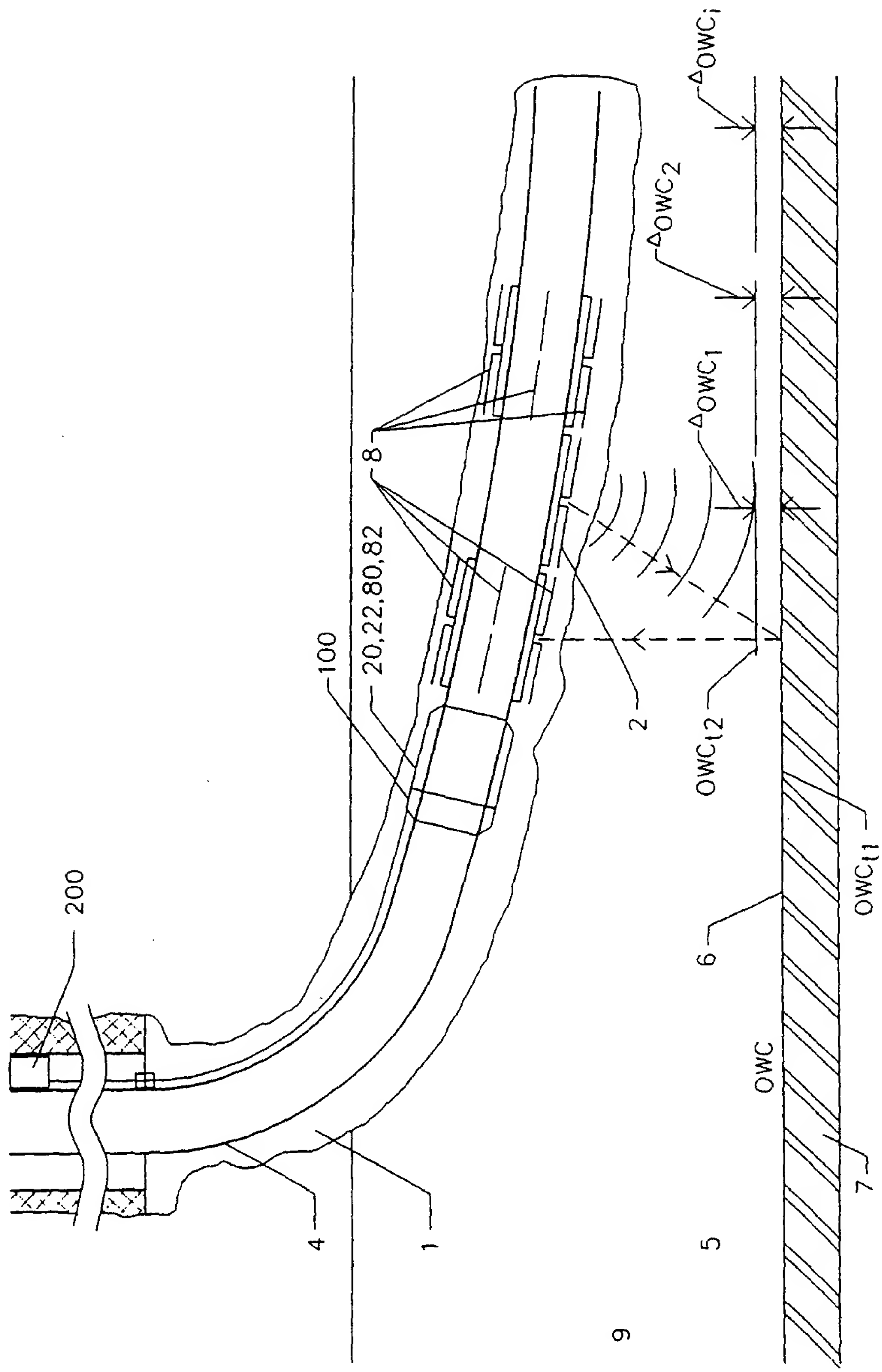

200
100
20,22,80,82
8
2
4
1
9
5
6
OWC
OWC$_{t1}$
OWC$_{t2}$
Δ_{OWC_1}
Δ_{OWC_2}
Δ_{OWC_i}
7

FIG. 8

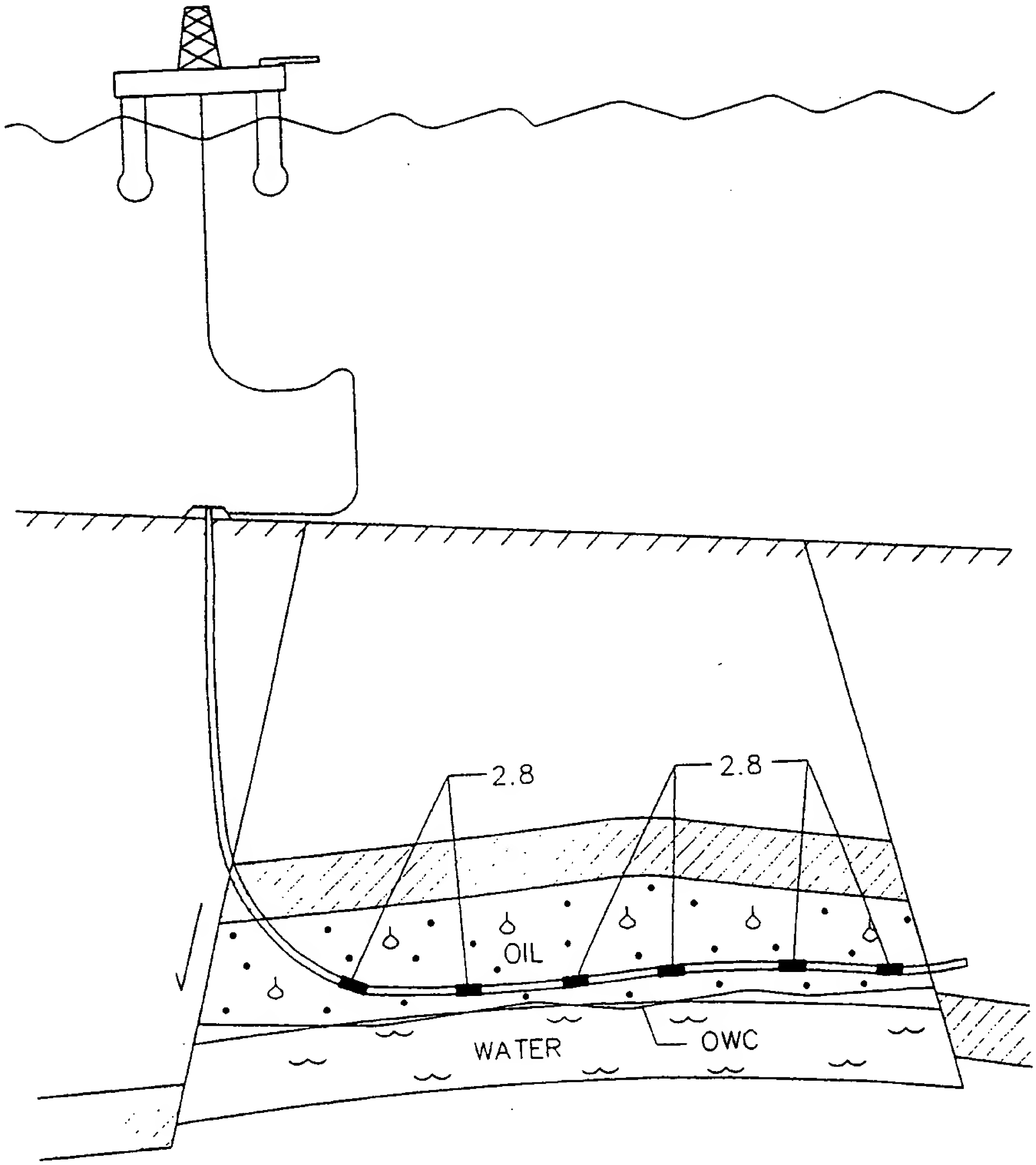


FIG. 9

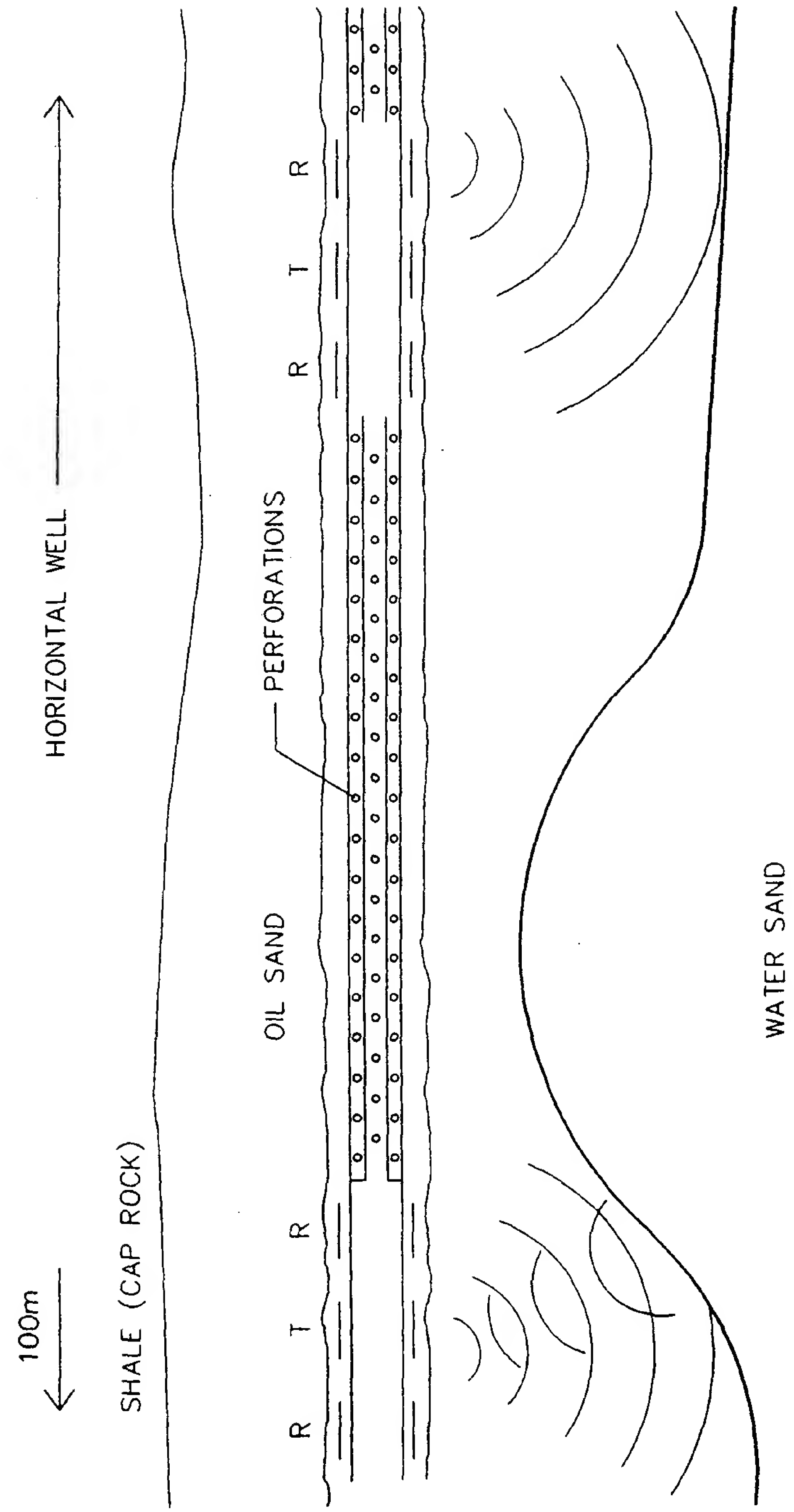

HORIZONTAL WELL
100m
SHALE (CAP ROCK)
PERFORATIONS
OIL SAND
R
T
R
R
T
R
WATER SAND

FIG. 10

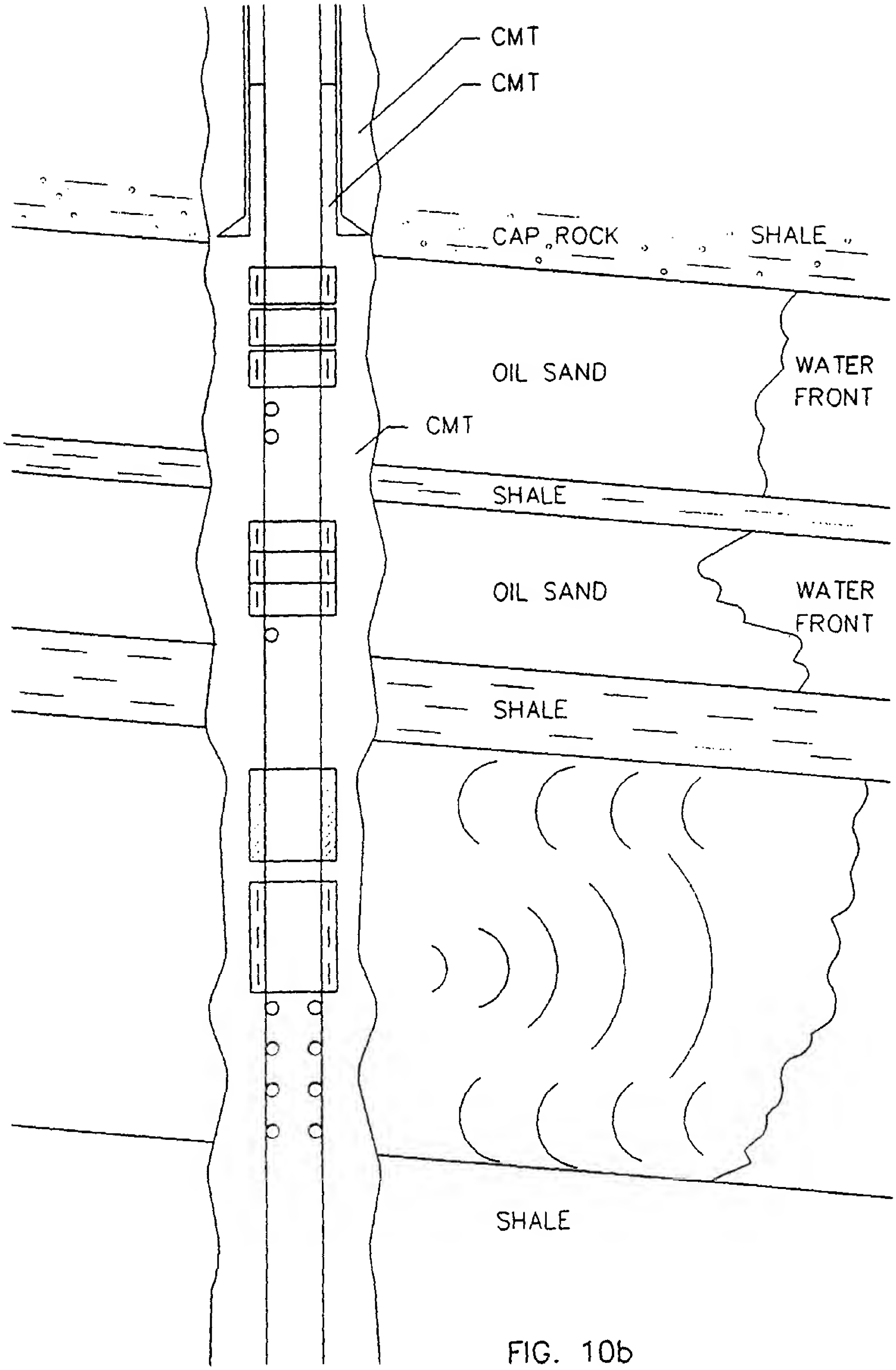

CMT
CMT
CAP ROCK
SHALE
OIL SAND
WATER FRONT
CMT
SHALE
OIL SAND
WATER FRONT
SHALE
SHALE

FIG. 10b

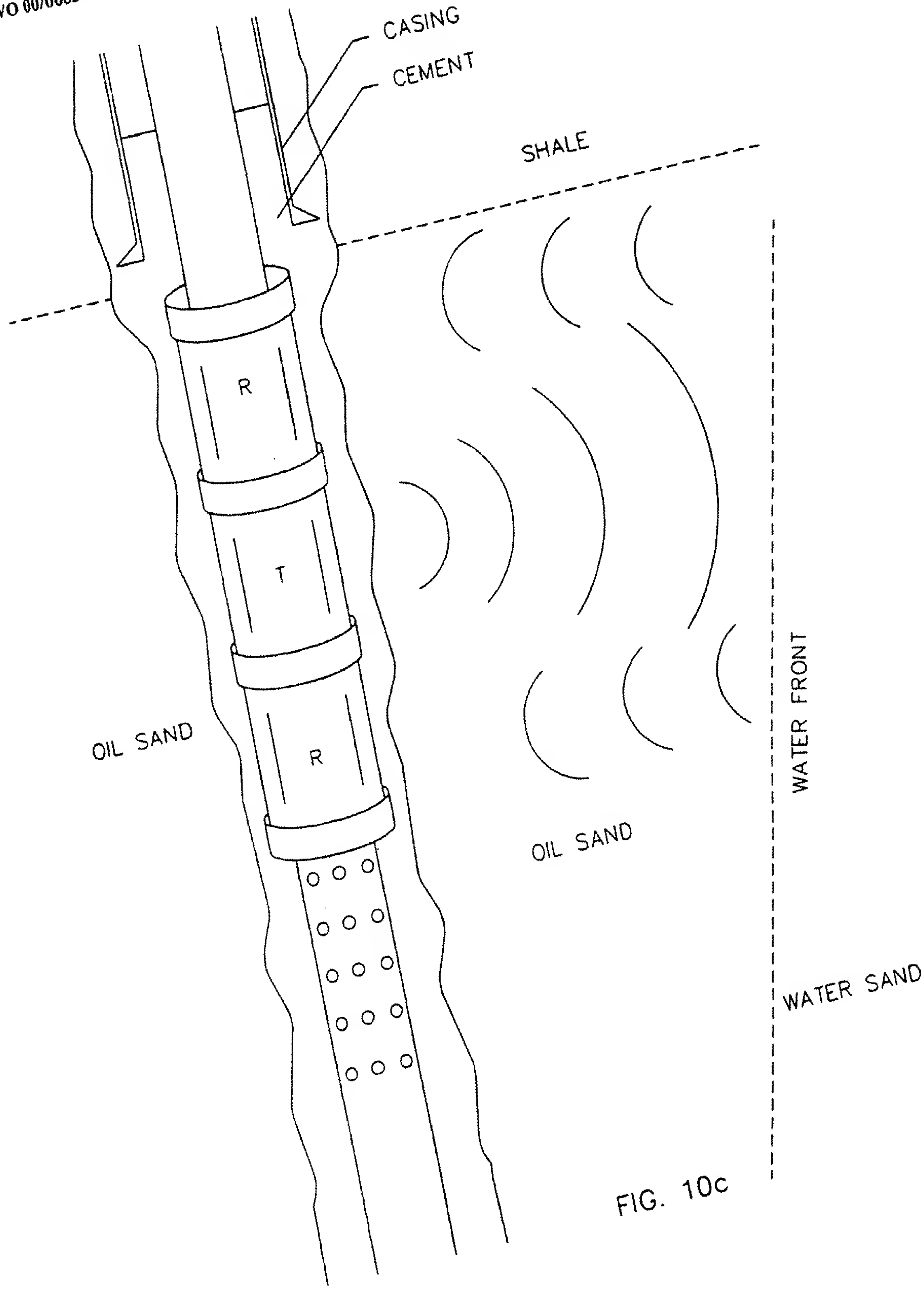

CASING
CEMENT
SHALE
R
T
R
OIL SAND
OIL SAND
WATER FRONT
WATER SAND

FIG. 10c

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NO 99/00206

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: G01V 3/30
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5860483 A (SVEN O. HAVIG), 19 January 1999 (19.01.99), column 1, line 65 - line 67; column 2, line 1 - line 31; column 5, line 25 - line 29, figure 1	1,18,38
	--	
A	US 5233304 A (CHRISTIAN HUBANS), 3 August 1993 (03.08.93), column 2, line 46 - line 57; column 4, line 12 - line 19, figures 1,2	1-38
	--	
A	US 5363094 A (PHILIPPE STARON ET AL.), 8 November 1994 (08.11.94), figure 1, abstract	1-38
	--	

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" erlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 November 1999	26 -11- 1999
Name and mailing address of the ISA/ Swedish Patent Office	Authorized officer

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5081419 A (RICHARD A. MEADOR ET AL.), 14 January 1992 (14.01.92), abstract --	1-38
A	US 5732776 A (PAULO S. TUBEL ET AL.), 31 March 1998 (31.03.98), abstract -- --------	1-38

INTERNATIONAL SEARCH REPORT
Information on patent family members

02/11/99

International application No.
PCT/NO 99/00206

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5860483 A	19/01/99	NO 301674 B	24/11/97
		NO 952072 A	25/11/96
		US 5892733 A	06/04/99
		US 5947199 A	07/09/99
US 5233304 A	03/08/93	AT 96233 T	15/11/93
		AU 644818 B	23/12/93
		AU 6581190 A	23/05/91
		CA 2029938 A	16/05/91
		DE 69004059 D	00/00/00
		DK 433110 T	07/03/94
		EP 0433110 A,B	19/06/91
		FR 2654521 A,B	17/05/91
		NO 176334 B,C	05/12/94
		OA 9271 A	31/08/92
US 5363094 A	08/11/94	CA 2085563 A	17/06/93
		DE 69209466 D,T	14/08/96
		EP 0547961 A,B	23/06/93
		FR 2685093 A,B	18/06/93
		JP 6505566 T	23/06/94
		WO 9312443 A	24/06/93
		FR 2688896 A,B	24/09/93
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		US 5672971 A	30/09/97
		US 5574374 A	12/11/96
		US 5811972 A	22/09/98
US 5732776 A	31/03/98	AU 708330 B	05/08/99
		AU 4980696 A	27/08/96
		AU 5022396 A	27/08/96
		CA 2187422 A	15/08/96
		CA 2187423 A	15/08/96
		GB 2302114 A,B	08/01/97
		GB 2302432 A	15/01/97
		GB 9621099 D	00/00/00
		GB 9621101 D	00/00/00
		NO 960518 A	12/08/96
		NO 960527 A	12/08/96
		US 5941307 A	24/08/99
		WO 9624747 A	15/08/96
		WO 9624751 A	15/08/96